Neuroplasticity of word learning

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Jedes Naturgesetz, das sich dem Beobachter offenbart,
lässt auf ein höheres, noch unerkanntes schließen.

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1. Language acquisition

1.1 Monolingual language acquisition

Language acquisition undergoes several modifications during lifetime. Most of the linguistic steps, however, are acquired during the first years of life. If we recall some phonological errors and mispronunciations children produce during early language production, it becomes evident how demanding and elaborate the single steps are. In the first weeks of life infants already produce first vocalizations such as crying, belching, coughing, sneezing, or gulping. Around 2 months they can produce single vowels and around 6 to 8 months they start the *babbling phase*. First, the same consonant-vowel pairs are repeated in succession and from 9 months onwards more complex syllables differing in consonant-vowel-pairs or stress patterns are created (Berndt, 1997). At this age, the vowel quality is influenced by the language spoken in the infants' surrounding and babbling sounds like the native language (de Boysson-Bardies & Vihman, 1991). Recent studies, however, showed that already cry melodies of newborn infants resemble the stress patterns of their native language (Mampe, Friederici, Christophe, & Wermke, 2009). In this study, French newborns cried with a final increasing melody whereas German infants cried with a decreasing pattern. Both melody contours correspond to the native language's stress patterns of iamb and trochee, respectively. Finally, at around 12 months of age infants usually produce their first word and start the *holographic phase* in which one-word-sentences are produced. At the beginning these words are mostly nouns and later on also verbs come along (Berndt, 1997). Around 18 months of age infants pass through the so-called *vocabulary spurt* or *naming explosion* (Goldfield & Reznick, 1990). At this age, a dramatic increase in word acquisition rate resulting in an acquisition of more than five words a day occurs (Fenson et al., 1994). At the same time the *telegraphic phase* begins in which infants combine two words to utter a sentence. This phase is followed by the *multi-word phase* around 20-24 months of age in which infants produce sentences containing different word categories such as nouns, verbs, a few prepositions and function words, but without any morphology so far (Berndt, 1997).

During the second year of life, vocabulary massively increases (Fenson et al., 1994). Even though the trajectories differ across infants, the vocabulary accumulated over the first 24 months can be an index for an elevated risk for developing specific language impairment (SLI). Usually, clinicians define the milestone to be reached at 24 months with 50 words (Smith et al., 2015; Zubrick, Taylor, Rice, & Slegers, 2007). If this number of words is not reached and no telegraphic phase was initiated, children are classified as "late talkers". Around 13% of 24-month-olds are late talkers. From these, however, around 30-50% are "late bloomers" who improve their language capacities in the following years. The remaining children, unfortunately, show deficits until school-age (Smith et al., 2015; Zubrick et al., 2007).

From 2 years onwards sensitivity to word order increases and children start producing abstract categories referring to distances, location, size, and time. Furthermore, the use of pronouns, auxiliaries, prepositions, definite and indefinite articles starts and longer sentences including subject, verb, and object are produced. Around 2 to 3 years also the use of morphological marker starts. At about 3,5 to 4 years more complex syntactic structures such as passive sentences, negation, and subordinate clauses are used (Berndt, 1997). After the age of 5 years, language development is indeed advanced but not terminated. Improvements will be achieved with respect to vocabulary, syntax, and morphology.

Furthermore, the use of adverbs, adjectives, irregular forms, comparative and superlative forms increases as well as advances with respect to passive constructions and subordinate clauses move on. The emergence of sophisticated pragmatic-communicative aspects also improves around this age (Berndt, 1997).

Even though word learning from the perspective of language production starts around the first birthday, speech perception already starts earlier. From the last months of gestation and after birth infants are confronted with the native language(s) spoken in their surroundings. At birth, newborns are equipped with the *"universal" ability to discriminate between different sounds* and can differentiate phonetic contrasts of all existing languages (Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Sebastián-Gallés, 2006, 2007; Werker & Yeung, 2005). A seminal study (Werker & Tees, 1984) showed that English infants could discriminate between two phonetically different sounds which corresponded to two Hindi phonemes during the first months of life, but that their ability declined towards the end of the first year, whereas Hindi infants maintained their ability as the phonemes were relevant for their native language (L1). Comparable results were replicated in a study (Kuhl et al., 2006) testing infants exposed to American English and Japanese during a phonetic discrimination task. The development of an enhanced sensitivity for features of the native language and the ability to differentiate them from an unknown language is an important prerequisite for learning words and vocabulary building (see *Native Language Magnet Theory expanded* – NLM-e – proposed by Kuhl et al., 2008). These changes in sensitivity with respect to native and non-native phonetic contrasts were subsumed under the term *perceptual narrowing*. The timeline for developing such perceptual narrowing for the native language(s) may differ for the linguistic feature in question but roughly occurs during the first year of life. It is important to note that these early steps into language correlate with later language abilities: a reduced sensitivity towards the native language features at a certain age seems to predict later language impairment (Kuhl et al., 2008).

One of the first abilities infants have to master when listening to a continuous speech stream is the segmentation into single units with the objective to identify where a word begins and where it ends and to assign the correct meaning to this word (Sebastián-Gallés, 2007). A large body of literature has shown that listeners rely on *prelexical cues* such as prosody (like word stress) (Cutler, 1996) and phonotactic constraints to segment the incoming speech stream and improve word recognition (Jusczyk, 1999). Stress pattern and phonotactics, thus, represent two fundamental abilities that have to be successfully acquired in the first years of life to "gate" further steps such as identification of words and the acquisition of vocabulary.

Prosodic cues are available at birth. Newborns are able to distinguish their native language from other rhythmically different languages (Mehler et al., 1988; Nazzi, Jusczyk, & Johnson, 2000). The more complex ability to discriminate the native language from a rhythmically similar language establishes around 4.5 months of age (Bosch & Sebastián-Gallés, 1997; Nazzi et al., 2000). *Stress pattern* describes a suprasegmental prosodic aspect on a specific syllable (Jusczyk, 1999). In detail, at the lexical word level, the most frequent stress pattern in bisyllabic words in languages such as English and German is the trochee (stress on the first syllable) (Cutler & Carter, 1987), while iambic stress pattern (stress on the last syllable), is predominant in other languages such as French. Behavioral studies demonstrated that around 7 to 9 months of age but not earlier infants prefer listening to the stress pattern of their native language (Jusczyk, Cutler, & Redanz, 1993; Jusczyk, 1999) and can use this linguistic factor to segment words out of sentences and thus identify word boundaries (Cutler, 1996).

Phonotactics governs segmental information. It describes the eligible combinations of different phonemes, in a given language (Trask, 1996). For example, /br/ is a possible or legal combination at the onset of a German or English word, whereas /bz/ is not (i.e., illegal). Several behavioral studies (Friederici & Wessels, 1993; Jusczyk et al., 1993; Mattys, Jusczyk, Luce, & Morgan, 1999; Mattys & Jusczyk, 2001) found that 9-month-old infants prefer listening to sound sequences which are legal with respect to their native language whereas 6-month-olds listen equally long to phonotactically legal and illegal sounds.

1.2 Bilingual language acquisition

Multilingual people are confronted with two or more languages. They have to deal with these different languages, being able to separate them from each other, and keeping these languages active. These increased demands have to be handled during language acquisition by means of effective cognitive control strategies. Monolingual newborns are capable of distinguishing two rhythmically different languages from birth (Mehler et al., 1988) and two rhythmically similar languages a few months later (Bosch & Sebastián-Gallés, 1997). When confronting bilingual infants with their native languages (two rhythmically similar languages such as Spanish and Catalan) and additionally with two unfamiliar languages such as English and Italian Bosch and Sebastián-Gallés (1997) could show that monolingual Spanish 4-month-olds and monolingual Catalan 4-month-olds more rapidly orient to their native language, whereas Spanish-Catalan bilingual infants at the same age show a preference for unfamiliar languages. This finding led to the conclusion that because bilinguals have to deal with two languages they first ascertain which of the two languages they hear, thus producing a delay in the orientation towards the native languages. This in turn confirms the early presence of inhibitory skills in bilingual infants. Similar findings were observed in a functional near-infrared spectroscopy (fNIRS) study (Petitto et al., 2012) investigating the sensitivity to native and non-native phonetic information in young (4-6 months) and older (10-12 months) monolingual and bilingual infants. Younger infants did not show activation differences between native and non-native phonemes nor between mono- and bilinguals. Older monolingual infants, however, showed a greater responsivity to native phonemes whereas bilinguals showed an equal activation for native and non-native phonemes. These findings suggest that bilingual children are more open for the acquisition of foreign languages, mainly originating from their increased experience with differential sounds. Based on these results Petitto et al. (2012) formulated the so-called *perceptual wedge hypothesis*.

These findings in bilingual infants challenge the *perceptual narrowing* assumption which occurs gradually in monolingual infants but was found to show also a U-shaped trajectory in bilingual language acquisition leading to an initial equal sensitivity to native and non-native contrasts around 4-5 months, followed by a decline in sensitivity for non-native contrasts around the end of the first year of life (similar to monolinguals) but afterwards a recurring equal sensitivity to native and non-native contrasts (Bosch & Sebastián-Gallés, 2003). These findings, however, have to be considered carefully as mostly found in Catalan-Spanish bilingual infants. These two languages show a high linguistic overlap, they share many cognates, and possess a similar rhythm possibly contributing to the found effects (Byers-Heinlein & Fennell, 2014).

Furthermore, the frequency of exposure to one language was also discussed as an important factor influencing bilingual language acquisition. Thus, the more linguistic input an infant gets, the higher is the sensitivity to native language contrasts. This account is supported by studies showing that bilingual 10-month-olds could discriminate between different stress patterns only if they were exposed enough time to the language in which these stress patterns are relevant (Bijeljac-Babic, Serres, Höhle, & Nazzi, 2012). These results fit with findings in adult second language learners (Dupoux, Sebastián-Gallés, Navarrete, & Peperkamp, 2008). However, considering that usually bilinguals have less exposure to each single language (even though the total amount of exposure to linguistic information is equal to monolinguals), it should be expected that they would also show delays with respect to monolingual language acquisition. Studies showed that this is not the case. The linguistic steps are acquired at almost the same time as in monolinguals (Bosch & Sebastian-Galles, 2001; Bosch & Sebastián-Gallés, 1997; Werker & Byers-Heinlein, 2008). They start producing their first words around 12 months and produce around 50 words at 18 months, thus resembling the same acquisition steps as monolinguals (Pearson, Fernandez, & Oller, 1993). Thus, even though language exposure plays a critical role during language acquisition, it is not the sole driving force.

Mattock, Polka, Rvachew, and Krehm (2010) have even found advantages of 17-month-old French-English bilinguals in a challenging word-object learning task when listening to words with small phonemic contrasts pronounced in either French or English. English and French monolinguals were not able to distinguish between these words probably because they are not so experienced in hearing sounds differing from their native language. An eye-tracking study in 12-month-old monolinguals and bilinguals could impressively show that bilinguals can learn two different kinds of linguistic regularities (ABA vs. AAB) whereas monolinguals can learn only one (Kovács & Mehler, 2009b). The authors concluded that bilinguals already at this early age are flexible enough in dealing with multiple speech structures. This seems to be a consequence of increased experience with differential inputs (i.e., bilinguals have to acquire twice as much as monolinguals in the same time) necessitating increased efficiency mechanisms. In the same vein of reasoning, it was found that 17-18-month-old bilinguals who knew more translation equivalents are more flexible learners of novel words and show faster lexical access probably because they are more used to listen to variable input (Byers-Heinlein & Werker, 2013; Poulin-Dubois, Bialystok, Blaye, Polonia, & Yott, 2013).

An important influence on bilingual language acquisition is the age of acquisition (AoA) of the second language (L2). Lenneberg's *critical period hypothesis* assumed that language can only be successfully acquired during a critical period in which the brain is most receptive for language processing (Lenneberg, 1967). He set this critical period between 2 and 13 years of age. Nowadays, we know that neither the beginning nor the end of this period must be considered such stringent and that also other influences such as the proficiency level attained (Rossi, Gugler, Friederici, & Hahne, 2006), motivational factors during language learning, and frequency of language exposure play a crucial role (De Groot & Kroll, 2014). However, an early AoA is still one determining factor for at least a less effortful learning environment than when learning a foreign language during adulthood.

1.3 Language re-acquisition after a brain lesion

After a brain lesion affecting language-related areas, often aphasia results as pathology. In 30% of patients having experienced a stroke an aphasia results (Engelter et al., 2006; Plowman, Hentz, & Ellis, 2012). Aphasia is "a cognitive disorder marked by an impaired ability to comprehend or express language in its written or spoken form. This condition is caused by diseases which affect the language areas of the dominant hemisphere" (ICD-10 classification R47.01, American Medical Association, 2017). The lesioned brain employs several plastic mechanisms to restore language functions at its best which in turn is influenced by the initial stroke severity and sometimes but not always by the site and size of lesion (Pedersen, Jørgensen, Nakayama, Raaschou, & Olsen, 1995; Plowman et al., 2012). The course of the aphasic symptoms change in the post-stroke period and are determined by the efficiency of neurophysiological remission mechanisms as well as the type and intensity of the speech therapy (Hartje & Poeck, 2002). The post-stroke period can be subdivided in an acute phase during the first 4-6 weeks. In this phase very fast and unexpected changes of the symptomatology (often improvements) occur. Partly during the acute phase and until the start of the chronic phase spontaneous remission takes place in which symptoms regress and a general improvement of linguistic functions is observable (the strongest advances occurring during the first 3 months). The chronic phase starts after 4-6 months but at the latest after 12 months post-stroke. During this period, symptoms get more stable and the four aphasic syndromes emerge (Broca-Aphasia, Wernicke-Aphasia, Global Aphasia, and Amnestic Aphasia) (Hartje & Poeck, 2002). At the neuronal level, neuroplasticity is extremely engaged during the various phases of aphasia recovery (Saur et al., 2006). During the first days after a left-hemispheric stroke a reduced activity of non-lesioned brain areas of the left hemisphere are observed. Around 2 weeks after stroke a taking over of homologous areas of the right hemisphere occurs as a major compensatory effect. After 4 to 12 months after stroke, thus during chronic phase, a reduction in activity of the right hemisphere and an increase in activity of perilesional areas of the left hemisphere are observed (Saur et al., 2006).

Neuroplastic changes can be furthermore supported by an intense language therapy, especially in the chronic phase where no spontaneous remission is expected anymore. Because one of the main symptoms in aphasia is the inability to name pictures/objects and in general to find the correct word in the lexicon, many therapies include a strong focus on training naming abilities. But also other specific deficits, especially at the phonological and syntactic level are addressed. Word re-acquisition mechanisms are not completely understood so far as influenced by several previously mentioned factors. Beneficial to language recovery is, however, an intense language therapy supported by computerized aids as well as brain stimulation methods (Allen, Mehta, McClure, & Teasell, 2012; Darkow & Flöel, 2016).

2. Word learning strategies

Infants but also adults who learn a foreign language or patients suffering from a brain lesion and having to re-acquire language use several word learning strategies to acquire language as fast and efficient as possible.

The American linguist Noam Chomsky postulated in his theory of *Universal Grammar* including the *Principle and Parameter Theory* (Chomsky, 1981; Chomsky, 1976) that each human being is endowed with innate cognitive and computational abilities (so-called Language Acquisition Devices) before concrete language experience which allow a fast language acquisition. He divided language in principles which are universal to all languages as well as parameters that vary across languages. Especially parameters such as the meaning of words are those features which have to be individually learned after birth. But how can they be learned and which strategies and mechanisms guide word learning?

2.1 *Merge* - a principle at the basis of word learning?

One principle adopted during language acquisition is the *Merge* operation assuming that language is formed by combinatorial rules (Berwick & Chomsky, 2015; Chomsky, 1995; Everaert, Huybregts, Chomsky, Berwick, & Bolhuis, 2015; Yang, Crain, Berwick, Chomsky, & Bolhuis, 2017). Thus, Merge is considered an innate recursive process in which e.g., X and Y are combined to XY which in turn can be combined with other terms. Such an assumption fits very well with the idea of language as a hierarchically structured system (Everaert et al., 2015). This principle is not only applicable to syntactic processing but also to phonological structures and word learning (Yang et al., 2017). In the context of phonology, a syllable consists of phonemes in an onset, nucleus, and coda position. Thus, phonemes can be combined to form a syllable. Syllables, in turn, can be merged to whole words exhibiting a specific stress pattern (i.e., a combination of strong and weak syllables) (Yang et al., 2017). Merge can occur during speech production in that infants' babbling merges linguistic units to create combinatorial structures, at the beginning using several phoneme combinations and later on using only those which belong to the native language (de Boysson-Bardies & Vihman, 1991). However, also speech perception is influenced by the combinatorial use of the native language as around the end of the first year of life infants lose their sensitivity to discriminate non-native phonemes (Werker & Tees, 1984).

The importance of such a general language learning mechanism becomes evident if we consider that only very few words are very frequently repeated in a specific language. Even though exposure to linguistic input is necessary for a successful language acquisition it does not seem to be exclusively responsible for. Infants cannot rely solely on the input, that is, the frequency of occurrence, to extract rules and learn words but they have to be able to generalize some few rules to other items. This assumption is also supported by neuroscientific data showing that even though the brain has a great storage capacity, this capacity cannot capture all possible linguistic combinations and idiosyncrasies due to computational limitations (Yang et al., 2017). Furthermore, children hardly get directly corrected by adults when they make linguistic errors. They will be just confronted with the correct form in a different linguistic experience and have to extract the correct form from this indirect negative evidence (Chomsky, 1981).

Thus, the assumed domain-general Language Acquisition Device postulated by Chomsky (1965) has to be highly structured allowing for such a rapid and accurate language acquisition. It relies on the distributional analysis of the linguistic input such as statistical learning, on probabilistic learning (i.e., the selection of a few more probable rules or words to be learned and ignoring inconsistent ones), and on computational efficiency (e.g., applying the easiest or shortest rule computation) (Yang et al., 2017).

2.2 Passive listening

In common to all learning strategies is that massive exposure to language input is important. During infancy massive exposure to language is usually easily achieved as parents and other surrounding people directly interact with the infant. During adulthood, we all know that a single foreign language course is not as effective as a longer stay in a foreign country where we are massively confronted with the foreign language from diverse modalities. Massive exposure to language, in general, was also found to be extremely important during the rehabilitation process after a brain lesion (Cherney, 2012; Darkow & Flöel, 2016). A language therapy for at least 3 weeks of at least 2 hours/day and at least 10 hours/week, plus at least 1 hour computer-based self-administered training per day, revealed beneficial effects for aphasic patients in the chronic phase (Baumgaertner et al., 2013).

Language can be acquired by mere exposure, thus through passively listen to the surrounding language input. This requires an intact acoustic organ or at least the possibility to acquire other language systems such as sign language. Hearing develops already in utero. Fetuses can already hear in the last trimester of pregnancy. However, they do not hear all frequencies as the womb acts as a low-pass filter through which only slow acoustic modulations such as prosody can be transmitted (Abrams & Gerhardt, 2000; Hall, 2000). This initial language learning is augmented after birth. One of the first challenges newborns are confronted with is to determine where a word begins and ends when listening to a continuous speech stream. Because no reliable acoustic cue indicates pauses between words, other mechanisms have to be applied. One important principle supporting learning via mere implicit passive exposure without concrete explicit instruction is *statistical learning* (for a recent review please refer to Aslin, 2017). Statistical learning describes learning about distributions without any feedback. A seminal study revealed the ability of 8-month-old infants to extract statistical probabilities between syllables from a continuous speech stream (Saffran, Aslin, & Newport, 1996). Intriguingly, this mechanism is operative already at birth (Gervain, Macagno, Cogoi, Peña, & Mehler, 2008; Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009) and is still present in older subjects (Cherry & Stadler, 1995). Furthermore, it is not restricted to rules learned during the actual presentation phase but rules can also be generalized to other contexts (Marcus, Vijayan, Rao, & Vishton, 1999). Statistical learning also occurs in other cognitive domains than language (thus can be considered domain-general) (Baldwin, Andersson, Saffran, & Meyer, 2008; Fiser & Aslin, 2002) and was found to function also in non-human species such as primates and rats (Conway & Christiansen, 2001; Toro & Trobalón, 2005). Despite this powerful learning mechanism, human beings' computational capacities are limited and we are not able to memorize all occurring statistical regularities in our environment.

Thus, constraints such as attention (e.g., overt instruction in adults or direction of gaze in infants), perceptual biases (e.g., stimuli adjacent in time are easier to be learned), prosody (e.g., stress patterns or infant-directed speech help segmenting the speech stream), and primacy and familiarity effects (e.g., more familiar stimuli or stimuli presented first in a learning session are more easily learned) limit the power of statistical learning but help accomplishing the learning challenge (Aslin, 2017).

Statistical learning was suggested to be strongly associated with memory encoding, storing, consolidating, and accessing processes (Gómez, 2017; Thiessen, 2017). While encoding takes place rapidly, consolidation is a more gradual process (Battaglia, Benchenane, Sirota, Pennartz, & Wiener, 2011; McClelland, McNaughton, & O'Reilly, 1995; Walker & Stickgold, 2006). It was found that infants in contrast to adults can better encode information that is irrelevant because they do not know what a relevant feature of a stimulus is and because their ability for attention control is restricted (Thiessen, 2017). These mechanisms are partially mediated by the development of prefrontal cortex (Diamond, 2000). Retention of newly learned information in memory, however, is much more fragile and limited in fidelity in infants below 15 months of age in contrast to adults (Gómez, 2017). This is connected to the differential developmental trajectories of the neocortex, the hippocampus, and corticostriatal system, all of them involved during statistical learning and learning in general (Gao et al., 2009; McClelland et al., 1995). It should be noted that the influence of memory is not restricted to statistical learning but also applies to semantic associative learning addressed in the subsequent section as well as in other learning processes.

Thus, infants are more open to different learning environments but at the cost of a slower pace (at least in real-world situations) while adults are more biased during learning but have developed efficient mechanisms to cope with. A good example is *perceptual narrowing* in which infants loose sensitivity to non-native phonemes but increase sensitivity to native ones (Kuhl et al., 2008; Werker & Tees, 1984).

2.3 Semantic associative learning

In order to learn the meaning of words, infants use several learning strategies. Apart from trying to extract regularities from the linguistic environment through passive listening, one other important strategy used for word learning is semantic associative learning. Here an object is associated with a specific word meaning. This process starts very early, prior to language production, and was termed *fast mapping* (Carey & Bartlett, 1978). Repeated presentation of a congruous word-object pair including distractors allow the infant to familiarize with this "correct" and to discard an "incorrect" association. Again statistical learning mechanisms play a role also during semantic learning (i.e., what is more frequently combined should be learnt). Fast mapping was found in infants around 12-14 months of age (e.g., Friedrich & Friederici, 2008; Smith & Yu, 2008) but some precursors to word-object learning in the sense of protoword learning was detected already in 3-month-olds by means of electrophysiological measures (Friedrich & Friederici, 2017). Fast mapping was shown to occur very fast, after only a few repetitions of the correct combination (Friedrich & Friederici, 2008). However, it is subject to strong influences from attention (Smith & Yu, 2013) and memory (Vlach & Johnson, 2013), impacting the learning process especially in infants who have immature systems.

Furthermore, fast mapping is associated by the amount of known words in the lexicon. Thus, the more words an infant has in the vocabulary, the more new words can be acquired (Smith, Suanda, & Yu, 2014).

Memorization of the newly learned associations is very important during fast mapping. Studies showed that even though very young infants can create an associative link their retention in memory is quite short. A recent study investigating fast mapping of object names and object properties in 3-4 year-old children show that while retention for object labels was still present one week later, retention for property labels such as color, shape, and texture was only present until 5 minutes after learning but vanished one week later (Holland, Simpson, & Riggs, 2015).

Capacities of mapping a new word to an object are also present in adulthood, especially when learning a foreign language (Breitenstein et al., 2005, 2007; Dobel, Junghöfer, et al., 2009).

Mapping a new word to an object is not as easy as it appears at first glance as it is impacted by several other constraints supporting efficient word learning. The *whole object constraint* describes that a new word primarily labels a whole object rather than single parts. The *noun-category bias* defines that a new word is assumed to extend to other members of the same category, and the *mutual exclusivity constraint* indicates that if an object has already a name the new word will refer to another object (Aslin, 2017; Carey, 1978; Markman, 1990; Markman & Hutchinson, 1984; Saffran et al., 1996).

Interestingly, word-object associative learning was found to be impacted by previous linguistic experience. Behavioral studies showed that infants between 14 and 19 months of age were able to learn word-object associations but only when words conformed to native language rules (both phonotactic constraints as well as stress patterns) but not through non-native rules (Graf Estes, 2014; Graf Estes & Bowen, 2013; Graf Estes, Edwards, & Saffran, 2011). These studies emphasize the importance of previous linguistic experience in shaping word learning.

The brain undergoes several plastic changes during fast mapping including fast neuronal changes occurring within minutes and hours as well as long-term plasticity related to synaptic plasticity (Morris et al., 2003; Segal, 2005).

For a successful fast mapping during infancy, the children have not only to process the verbal part of the input, namely the new word, but they also have to memorize the object in order to associate the new word with the new object. To do this, the features of objects must be identified allowing for a distinction between different objects. Fast mapping in infants is thus very different from fast mapping during later childhood or adulthood because mostly the objects are already familiar and only the new word must be learned and associated to the already known object. In adults, especially ventral brain areas and in particular the anterior part of the temporal cortex are responsible for processing features and thus semantic information of an object (Cloutman, 2013; Humphreys, Price, & Riddoch, 1999; Peelen & Caramazza, 2012). The development of object processing during infancy starts very early. Infants can individuate objects by features, but they are initially (~4.5 months) more sensitive to shape differences and afterwards (~11.5 months) get also sensitive to surface features such as color (Wilcox, 1999). It was furthermore shown that surface features must be functionally relevant in order to be processed (Wilcox & Chapa, 2004). Interestingly, even though object features are processed quite early, the retention of these features is still immature at 24 months of age (Perry, Axelsson, & Horst, 2016).

2.4 Infant-directed speech

Even though infant-directed speech (IDS) is not a word learning strategy per se it provides an important support during word learning as it emphasizes relevant speech input and thus guides attention towards the current (to be learned) stimulus. Infant-directed speech is characterized by an exaggerated pitch, longer duration of words, the use of simpler words, as well as a high phonological clarity during pronunciation (Kuhl et al., 1997; Soderstrom, 2007). On an acoustic level, F1 and F2 formants are different for many vowels resulting in a larger vowel space (Burnham, Kitamura, & Vollmer-Conna, 2002; Uther, Knoll, & Burnham, 2007). All these features also affect emotional aspects of the interaction between the speaker and the listener (Uther et al., 2007). Especially the prosodic features of IDS aid segmentation of the acoustic speech stream into single units, thus an infant can better identify where a word begins and ends (Singh, Nestor, Parikh, & Yull, 2009). It was shown that infants prefer listening to IDS compared to adult-directed speech (ADS) and that vocabulary growth and speech processing in general are speeded-up (Cooper & Aslin, 1994; Pegg, Werker, & McLeod, 1992; Saffran et al., 1996; Weisleder & Fernald, 2013). Despite these beneficial effects of IDS, there are some few cultures worldwide which do not possess such a speech mode when speaking to infants. Kaluli, for example, is a language of Papua New Guinea which does not differentiates between speaking to adults or infants and no negative effects on language acquisition were observed (Schieffelin, 1979). Thus, IDS can assist language learning but it seems not to be a necessary prerequisite for successful acquisition.

It is not clear so far, how long infants show an increased sensitivity to IDS. Some studies report a U-shaped trajectory showing an initial sensitivity which reduces around 9 months of age and becomes again available in the subsequent months but others do not show a recovery from the insensitivity around 9 months (Soderstrom, 2007). However, also the insensitivity to IDS around 9 months of age could not be reliably replicated (Naoi et al., 2012) suggesting that the impact of IDS is not only determined by the infants' age but is influenced by several factors such as e.g., the familiarity to the voice speaking in IDS mode or the setting in which IDS occurs.

IDS was found to elicit differential electrophysiological correlates already in newborns (Bosseler, Teinonen, Tervaniemi, & Huotilainen, 2016) as well as to recruit differential brain areas, especially frontal areas, in infants (Naoi et al., 2012).

2.5 Socio-pragmatic skills

Language learning in infants, children, and adults is influenced by socio-pragmatic skills. The essence of language is to allow for a communication between people. This is already successfully expected by young infants (Ferguson & Waxman, 2016). At around 9 months infants already use gestures to indicate the intention for example to reaching for an object. In doing so they attract attention of other people and direct their behavior (Bates, 2014).

But not only the own use of pragmatic skills is important during communication but also to interpret socio-pragmatic information performed by others is crucial especially during word learning. Infants and children can learn novel words for an object by inferring the intended object from the speaker's gaze (Baldwin, 1993; O'Connell, Poulin-Dubois, Demke, & Guay, 2009; Tomasello, 1988), from pointing (Paulus & Fikkert, 2014), retracing contours (Hansen & Markman, 2009), or referent-related actions (Kobayashi, 1998).

Gestures have another important function in aiding language learning in infants but also in adults (Kang & Tversky, 2016; Krönke, Mueller, Friederici, & Obrig, 2013; Macedonia & Mueller, 2016). Furthermore, a gesture training was found to have beneficial effects in some subgroups of aphasic patients (Kroenke, Kraft, Regenbrecht, & Obrig, 2013). Learning words and phrases through gestures was found to enhance memory retention, thus a link with memory was assumed (Nyberg et al., 2001). Furthermore, when looking at gestures concomitant to a newly presented word, the audio-visual interaction impacts word retention (Paivio, 1969). Such audio-visual combinations were found to be used already in young infants (Shaw, Baart, Depowski, & Bortfeld, 2015). A further impact of gestures is assumed with respect to attention processes as it enhances retention (Muzzio, Kentros, & Kandel, 2009; Pereira, Ellis, & Freeman, 2012).

3. Neuroplasticity of language processing

3.1 Methods for assessing brain activity

Several extremely valuable behavioral methods such as high sucking rate, head turn preference, looking times, and reaction time experiments provided and still provide important findings with respect to a better understanding of mechanisms underlying language acquisition and language learning during infancy, childhood, and adulthood. However, most of these methods are suitable for measuring subjects of specific age groups and do not allow using the same methodology over lifetime. Neuroscientific methods can fill this gap as applicable in infants as well as in adults. Furthermore, as Chomsky (1965) already stated there is a difference between linguistic *competence* and *performance*. The former refers to the knowledge one person possesses while the latter describes the use of this linguistic knowledge in communication. Considering this dichotomy in light of neuroscientific methods the brain can show a specific knowledge (i.e., reflected in a distinctive neuronal response between experimental conditions) which however does not necessarily have a clear behavioral appearance. Furthermore, some behavioral responses are delayed compared to some brain mechanisms as a consequential delay is present from the processing initiation in the brain and the actual behavioral execution for example by pressing a button. Thus, at least with electro- or magnetoencephalographic measurements processing can be assessed in the range of milliseconds thus capturing ongoing online mechanisms. A further advantage of neuroscientific methods in contrast to some behavioral measures is that usually no attention is needed thus allowing to assess implicit processing mechanisms and even mechanisms during states of reduced consciousness like during sleep.

Given the undoubtable value of behavioral measures I am of the opinion that the most suitable method should be selected with respect to the research question under investigation. Also neuroscientific methods do not always reliably detect processing mechanisms due to their underlying different technologies often sensitive to different neurophysiological mechanisms. Thus, I am a supporter of *multi-methodological approaches* combining - if possible - either behavioral with neuroscientific or several neuroscientific methods. In many of the experiments presented in this habilitation treatise I simultaneously applied the two neuroscientific methods of electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) as they are easily combinable in the same EEG cap, because they do not interfere with each other, because they are soundless measures allowing for the analysis of fine-grained acoustic differences, and finally because they provide a quite natural experimental setting and are well tolerated, especially by infants sitting on a parents' lap during the experiment. An overview of the advantages and limitations of each method can be find in Figure 3.1, taken from the first article presented here (Rossi, Telkemeyer, Wartenburger, & Obrig, 2012). In Experiment 2 a combination of EEG and a voxel-based-lesion mapping approach on the basis of structural MRI scans of the subjects' brains was applied.

In the following I will introduce the neuroscientific methods used in the following experiments.

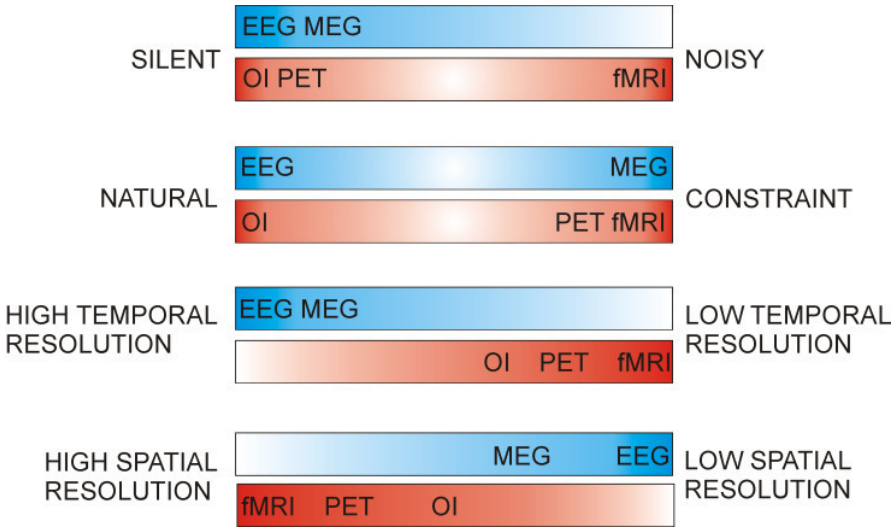

Figure 3.1. Advantages and limitations of neuroscientific methods
(permission for reproducing this figure from Rossi et al. (2012) was granted)
EEG (electroencephalography), MEG (magneto-encephalography), OI (optical imaging)
PET (positron-emission-tomography), fMRI (functional magnetic resonance imaging)

3.1.1 The electroencephalography

The electroencephalography (EEG) is a non-invasive method assessing the electric activity of the brain from the scalp by means of voltage differences between electrodes. The method has an excellent temporal resolution in the range of milliseconds and is thus suitable for assessing fast online processing mechanisms as occurring during language processing or language learning. Because the signal is measured from the scalp and the brain regions generating the signal do not necessarily have to reside below the measuring electrodes (please refer to the inverse problem of the EEG, Wendel et al., 2009), the topographical resolution is limited with this method.

The neurologist and psychiatrist *Hans Berger* first measured voltage fluctuations in dogs and cats in 1902. In 1924 he succeeded in measuring first voltage fluctuations from the human cortex (Stern, Ray, & Quigley, 2001). The signal measured from the scalp consists of the summation of synchronous activity of several neurons having the same vertical orientation. Ion movements in the dendrites and the soma of the pyramidal cells lead to a dipole (i.e., reversed charges in dendrite and soma) eliciting field potentials which can be assessed from electrodes positioned on the scalp (Birbaumer & Schmidt, 2006). Usually, these electrodes are made of AgAgCl and nowadays integrated in a cap or net of different sizes. This allows to measure many (i.e., 32, 64, 128 or even 256) electrodes covering brain areas of interest. Additionally, a reference electrode is needed to subtract this activity from each electrode on the scalp (i.e., monopolar recording or common reference) in order to measure voltage differences. A ground electrode is furthermore necessary to minimize individual electrostatic charge (Rugg & Coles, 1995; Stern et al., 2001). Electrode placement is realized in accordance with the 10-20 placement system arranging electrodes in 10% or 20% distance from the nasion to the inion and between the two preauricular points (Jasper, 1958; Sharbrough et al., 1991).

Internationally, standard nomenclature for the single electrodes is used: F - frontal, C - central, T - temporal, P - parietal, O - occipital. Electrodes over the left hemisphere are further coded with odd numbers (increasing from superior to inferior), over the right hemisphere with even numbers, whereas midline electrodes include a Z for zero.

Several analyses methods can be applied to EEG data (e.g., frequency bands and power spectra). One analysis method relevant for assessing fast dynamic changes with respect to the time-locked signal of different types of stimulation is *event-related brain potentials* (ERPs). ERPs can arise before, during, and after acoustic, visual, or other sensorial stimulations. Because over the course of an experimental session background activity superimposes the time-locked signal to specific stimulations, ERPs have to be extracted from this noisy spontaneous signal. This is done by means of the averaging technique in which several signal segments before and after the stimulus onset belonging to the same experimental condition are averaged. Thus, the similar electrophysiological activity elicited through the repeated presentation of the same stimulus category is extracted from the randomly distributed noise (Picton, Lins, & Scherg, 1995; Rugg & Coles, 1995). The result of this averaging technique is an ERP component for each experimental condition which can be described according to its polarity (negative or positive), latency with respect to stimulus onset, topography on the scalp, and sensitivity (i.e., change induced by the experimental manipulation) (Donchin, Ritter, & McCallum, 1978).

3.1.2 The functional near-infrared spectroscopy

The functional near-infrared spectroscopy (fNIRS) is an optical imaging technique assessing vascular changes. It uses near-infrared light to assess oxygenation changes in the blood. By means of light emitters near-infrared light is sent from the scalp to the subjacent tissue. Some photons are absorbed by the tissue but some others are reflected and can be collected by light detectors at the scalp. It is known that near-infrared light in the wave length between 600 and 1000 nm passes through biological tissue because it is relatively transparent, because oxygenated and deoxygenated hemoglobin have characteristic absorption spectra that allow a spectroscopic differentiation, and because changes on the cerebral tissue lead only to small changes in scattering characteristics (Obrig & Villringer, 2003). Hemoglobin is an iron-containing protein complex which binds and transports oxygen in the erythrocytes of the blood. Hemoglobin changes its color in dependence of the amount of oxygen. The physiological basis of fNIRS is the *neurovascular coupling* assuming that if a brain region is more active during a specific stimulation, thus an increase in neuronal activity occurs, several vascular and metabolic changes appear: vasodilation leads to a local increase in blood volume demanding more oxygen and glucose which lead to an increase in regional cerebral blood flow and an increase in regional blood flow velocity (Logothetis & Wandell, 2004; Uludağ et al., 2004). Consequently, the color of the blood changes. The blood flow increase overcompensates oxygen consumption and elicits a focal hyperoxygenation resulting in an increase in oxygenated hemoglobin (HbO) as well as a decrease in deoxygenated hemoglobin (HbR) (Fox & Raichle, 1986). Both are indications of neuronal activation. The conversion from recollected reflected light into concentration changes of hemoglobin is achieved by the Lambert-Beer-law (Cope, Delpy, Wray, Wyatt, & Reynolds, 1989; Reynolds et al., 1988). It should be noted that HbR is inversely correlated with the blood-oxygen-level-dependent (BOLD) response assessed by functional magnetic resonance imaging (fMRI), thus more directly comparable to fMRI findings (Kleinschmidt et al., 1996; Obrig & Villringer, 2003).

Several fNIRS light emitters and detectors can be arranged at about 3 cm distance allowing for assessing neuronal activation in 2-3 cm depth from the scalp (i.e., covering about 1 cm of cortical surface). Increase in distance between emitter and detector would result in a deeper coverage but also in more light absorption. In infants, light might penetrate into deeper structures due to the smaller head circumference but because boundaries between cerebral spinal fluid and gray and white matter "channel" the light, also in infants mainly cerebral areas can be reliably assessed (Okada & Delpy, 2003). However, due to the thin skull of infants, signal-to-noise-ratio is definitely higher. FNIRS probes can be integrated in a commercially available EEG cap allowing to use at least some electrode positions from the 10-20 placement system as orientation and thus allowing for more standardized positioning. Figure 3.2 shows a combined EEG and fNIRS setup in an infant.

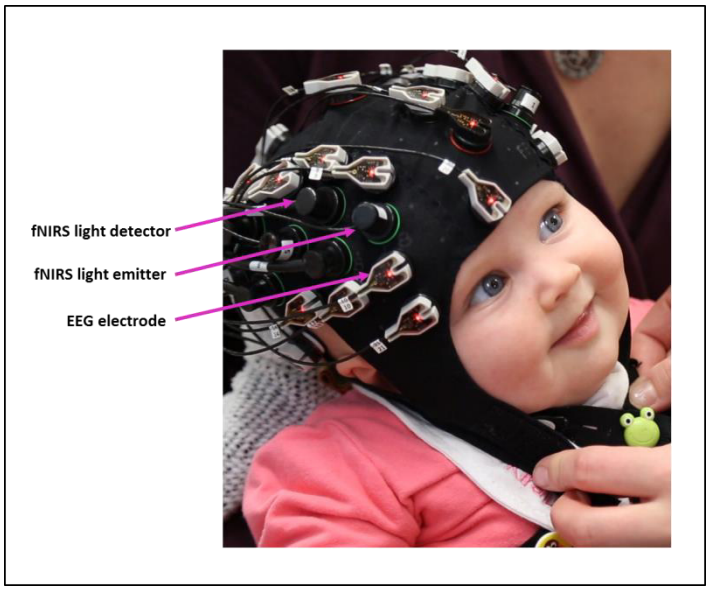

Figure 3.2. Simultaneous EEG and fNIRS application in an infant (parents' permission to show the photograph was obtained).

fNIRS shows several advantages compared to other imaging techniques such as fMRI: (1) it provides a quite natural environment in which fNIRS probes are integrated in a cap and allow the participant to sit on a comfortable chair or lie in a bed or in the case of infants to sit on the parent's lap or in a buggy, (2) it does not induce any instrumental noise such as MRI and thus allows for the investigation of fine-grained acoustic stimulation, (3) it has a better temporal resolution compared to fMRI, and (3) it does not interfere with other methods, thus it allows for the simultaneous application, for example with EEG without any difficulty.

3.1.3 The magnetic resonance imaging

Magnetic resonance imaging (MRI) is an imaging procedure to visualize anatomical structures of the body with high spatial resolution. The device consists of a narrow magnetic tube (usually of 1.5, 3, or more Tesla magnetic field strength) in which subjects or patients lie. Depending on which part of the body is examined the subject has to be specifically placed inside the magnetic resonance scanner. Particularly, for brain imaging an additional head coil has to be positioned around the head of the subject.

The physical principle of MR imaging is to measure the proton distribution in the human body by measuring the nuclear spin rate. Each atom nucleus (in the brain mostly protons) have a quantum property of a spin (i.e., in a classical picture resembling a rotation around their axis) and thus have a non-zero magnetic moment. If these atoms are located in a strong external magnetic field spin state can change and they tend to align more parallel to the external magnetic field. Because the spin axis is not perfectly parallel to the external magnetic field a motion of precession of the spin occurs. The precessional frequency can be calculated from the Larmor equation and is called Larmor frequency. At this frequency, which is typically in the radio frequency range and assessed by means of the head coil, energy can be transferred in a resonant process to the atom nuclei and their spin states may change to a different energy level. This goes along with a change in the net macroscopic magnetization, which can be recorded (Weishaupt, Köchli, & Marincek, 2006).

In order to assess single slices in a three-dimensional space additional gradient coils are used which impact the magnetic field strength along the x-, y-, and z-axes. In this case, the spatial position of a recorded signal corresponds to the resonance frequency which is a function of the magnetic field strength. The spatial identification of the MR signal is thus accomplished by spatial encoding (for details please refer to Weishaupt et al., 2006). The signal strength recorded in each vowel results in a color-coded image in grey nuances.

The great advantage of MRI is that soft tissue such as in the brain can be excellently visualized in contrast to other imaging techniques. The spatial resolution is in the range of millimeters. However, some limitations are also present: (1) it represents a quite unnatural environment in which a participant has to lie as still as possible in a narrow scanner tube thus limiting bedside or applications in young infants, (2) the changing magnetic fields of the gradient coils generate a loud banging sound necessitating hearing protection and thus limiting the application of experimental settings presenting fine-grained acoustic stimuli, and (3) the strong static magnetic field interferes with other electrical methods such as EEG.

Several analyses methods can be applied to MRI scans such as structural MRI, voxel based morphometry, resting-state MRI, diffusion tensor imaging, and functional MRI.

In Experiment 2 of this habilitation treatise behavioral but more importantly ERP data were correlated with lesion-based data from structural MRI scans of patients suffering from a left-hemispheric brain lesion. This approach represents an extension of the *voxel-based lesion-symptom mapping* (VBLSM) (Bates et al., 2003) in that ERPs instead of behavioral measures were correlated with the lesion topography. A high-resolution structural MRI scan is acquired for each patient in order to assess the extent of the lesion. Lesion delineation was performed manually in each patient in all planes (axial, coronal, and sagittal) for each slice of the T_1 image (i.e., based on realignment of spins to the longitudinal magnetization). Each voxel is then coded binary (lesioned or not lesioned) and afterwards correlated with ERP differences acquired during an EEG experiment.

3.2 Language-related brain regions and hemispheric lateralization

3.2.1 Language topography in the adult brain

Language processing in the brain recruits a brain network of several brain regions including frontal, temporal, and parietal areas. Two classical "language areas", historically identified to support language functions are Broca's area in inferior frontal regions and Wernicke's area in temporal regions. With increasing advances in neuroimaging techniques, this dichotomous classification was softened and a broader and more detailed network identified supporting processing of different linguistic features (for a recent review on some controversies with respect to Wernicke's area please refer to Binder, 2017). I will focus on brain regions relevant during word learning.

Phonological and lexico-semantic aspects play a crucial role during word learning. Single phonemes have to be identified and combined to phonological word forms which can afterwards be accessed in the lexicon. Finally, the meaning of a word can be retrieved. These processes are assumed to be primarily supported by temporal areas, especially in superior temporal gyrus (STG) and superior temporal sulcus (STS), which are however also interconnected to inferior frontal areas (Hickok & Poeppel, 2015; Skeide & Friederici, 2016; Vigneau et al., 2006). In particular, phonological processing was found to elicit activations in the posterior part of STS/STG (Binder, 2017; Hickok & Poeppel, 2007) whereas lexico-semantic processing predominantly recruited the middle temporal gyrus (MTG) (Binder et al., 1997; Binder, 2017; Rissman, Eliassen, & Blumstein, 2003). Frontal and temporo-parietal areas are connected via several fasciculi which were mainly subdivided in a dorsal and a ventral stream. The dorsal stream connects temporal to frontal area via the superior longitudinal fasciculus including the arcuate fasciculus whereas the ventral stream connects these brain areas via the inferior fronto-occipital fasciculus and the inferior longitudinal fasciculus (Friederici, 2015; Hickok & Poeppel, 2015; Sarubbo et al., 2015; Skeide & Friederici, 2016). Dorsal pathways are assumed to support the mapping from sound to action relevant for auditory-motor integration during speech production (Hickok & Poeppel, 2007, 2015), phonological processing (Sarubbo et al., 2015) as well as syntactic and combinatorial processing as reflected in the Merge principle (Friederici, 2015; Zaccarella, Schell, & Friederici, 2017). The ventral stream on the other hand seems to support the mapping from sound to meaning allowing access to the lexicon and thus supporting lexico-semantic processing (Friederici, 2015; Hickok & Poeppel, 2015; Skeide & Friederici, 2016).

In order to successfully learn words and retrieve their correct meaning also socio-pragmatic cues such as the correct interpretation of communicative intent are necessary. Identifying communicative intentions by means of gestures or other visual cues was found to be supported by a brain network including the STS, the temporo-parietal junction (TPJ), as well as prefrontal regions (Enrici, Adenzato, Cappa, Bara, & Tettamanti, 2010).

Executive functions are necessary to efficiently adapt to new environmental challenges, especially during learning. They represent a conglomerate including functions such as salience detection, monitoring, attention, working memory, shifting, and inhibition (Dajani & Uddin, 2015; Miyake et al., 2000). The brain network supporting executive functions includes fronto-parietal brain regions such as the prefrontal cortex, the anterior cingulate, the right anterior insula, the inferior and superior parietal cortices, the inferior temporal cortex, the occipital cortex as well as the caudate and thalamus (Dajani & Uddin, 2015; Niendam et al., 2012).

Executive functions seem to play a crucial role during learning multiple languages. Because bilinguals constantly train switching between languages, usually keeping both languages active, at least at a certain degree, but inhibiting the momentarily not used language, their executive functions were found to be superior in contrast to monolinguals (for a recent review cf. for example Buchweitz & Prat, 2013). This was found already at 7 months of age (Kovács & Mehler, 2009a) but also at an age of 24 months (Poulin-Dubois, Blaye, Coutya, & Bialystok, 2011), during adulthood (Costa, Hernández, & Sebastián-Gallés, 2008), and finally during aging (Bialystok, Craik, Klein, & Viswanathan, 2004). This specific bilingual experience was found to induce transfer effects across cognitive domains, especially from executive functions to language. Thus, similar processing mechanisms impact both domains and are accompanied by overlapping neuronal correlates (Abutalebi & Green, 2007; Li, Legault, & Litcofsky, 2014; Liu, Fan, Rossi, Yao, & Chen, 2015; Liu, Rossi, Zhou, & Chen, 2014).

It is well known that language functions are lateralized. Around 90% of all right-handed people show most dominant linguistic functions in the left-hemisphere (Karnath & Thier, 2012). However, not all language functions recruit the left hemisphere but also the right hemisphere contributes to language processing. The *Dynamic Dual Pathway model* (Friederici & Alter, 2004) postulates that segmental information such as phonology, lexicon, and syntax recruit the left hemisphere whereas suprasegmental functions such as prosody are predominantly processed in the right hemisphere. Linguistic functions relevant during word learning mainly include phonology and lexico-semantic processes. These functions are largely localized in a fronto-tempo-parietal network of the left hemisphere in adult brains. The *multi time resolution hypothesis* (Poeppel, Idsardi, & van Wassenhove, 2008) focusing on the processing of acoustic stimuli in general, postulates a left or sometimes more bilateral organization for fast acoustic transitions (~25 ms) and a predominantly right-hemispheric lateralization for slow variations (~250 ms). Because fast transitions in language occur for example in formant transitions relevant for distinguishing between different phonemes and slow variations correspond to prosodic aspects of language, this bilateral/more left versus right lateralization idea also conforms to the assumptions of the Dynamic Dual Pathway model.

3.2.2 Language topography in the developing brain

The tuning into language functions during language acquisition is accompanied by neuroplastic changes in the brain determined by the development of specific brain regions. Most changes occur in the first years of life. Some capacities such as the discrimination of different phonemes is already present a few weeks before birth and recruits similar brain areas in superior temporal and inferior frontal areas as in adults (Mahmoudzadeh et al., 2013). Furthermore, other capacities necessary for segmenting the acoustic speech stream into single units (such as relying on prosodic aspects) are operative in newborns and were found to recruit the mid STG of the right hemisphere (Perani et al., 2011). The ability to associate word forms with objects and access and retrieve word meaning from the lexicon is also present quite early. Around 12 months of age these processes are supported by an adult-like network of middle and superior temporal cortices (Travis et al., 2011). These findings are supported by studies showing that some anatomical white matter fibers (especially the ventral and the dorsal pathway connecting temporal areas to premotor areas) are already present at birth (Perani et al., 2011). Other dorsal connections from temporal to inferior frontal areas supporting syntactic processing, however, develop later on (Brauer, Anwander, & Friederici, 2011).

Even though semantic processing is present quite early during infancy, it is subject to further specialization during childhood. This improvement of semantic processing goes along with an increase in activation in inferior frontal and middle temporal areas (Weiss-Croft & Baldeweg, 2015).

Executive functions which are crucial for successful language learning are also subject to developmental changes, however, the fronto-parietal network underlying executive functions was found to be adult-like at birth (Doria et al., 2010). Contrary to the obsolete assumption that the frontal cortex matures later in contrast to other brain areas, Leroy et al. (2011) found a stronger maturation already during the first months of life. This is crucial as this area is strongly involved in human learning and executive functions. Nevertheless, differential subcomponents still mature throughout childhood and adolescence until they reach the same effective application as in adults. Inhibition, for example, develops around 12 months of age but is mature around the age of 10-12 years (Dajani & Uddin, 2015). Considering neuronal changes in general, an increased recruitment of right lateralized brain regions was found in adults compared to children (Rubia et al., 2006). We could find a similar developmental pattern adopting the functional near-infrared spectroscopy (fNIRS) to track activation changes with respect to inhibitory control during a go/no-go-task in 4-6-year-old children (Mehnert et al., 2013). We found an increase in functional connectivity within the right frontal lobe with increasing age. Furthermore, children showed a stronger reliance on frontal areas whereas adults included the whole fronto-parietal network. This might be due to the stronger inhibition and working memory demand and thus stronger recruitment of frontal areas in contrast to adults. These findings fit with the assumption of a shift from anterior to posterior brain areas as abilities become more automatized with increasing experience (Jeon & Friederici, 2015; Johnson, 2001).

Hemispheric lateralization for language is also a highly debated issue in current research. It is not clear whether lateralization is present from birth on or whether it develops during language acquisition. Several studies found already a left-hemispheric specialization at birth or during the first months of life. When listening to connected speech presented either forward or backward (i.e., the audio file was digitally reversed), newborns (Peña et al., 2003) as well as 3-month-olds (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002) showed a clear left-hemispheric recruitment for forward speech. Similarly, 3-month-old infants listening to normal sentences (i.e., containing phonology, semantics, but also prosodic aspects) elicited a stronger right-hemispheric activation than for aprosodic sentences (i.e., sentences which were digitally flattened in such a way that no prosodic information was present anymore) (Homae, Watanabe, Nakano, Asakawa, & Taga, 2006). We also investigated lateralization in newborns by means of fNIRS while they listened to 9 s long acoustic stimuli varying in their temporal acoustic features (slow versus fast varying features). Fast temporal variations gave rise to a bilateral recruitment whereas slow modulations elicited a right-hemispheric dominance (Telkemeyer et al., 2009). This study confirmed that assumptions put forward by the multi-time resolution hypothesis (Poeppel et al., 2008) are also valid in newborn infants. These studies emphasize that hemispheric specialization seems to be innate or at least present very early in life. Another line of studies, however, contradicts this idea showing that lateralization develops later on during language acquisition and is thus impacted by maturational constraints. A lexically relevant linguistic manipulation in single words was found to be differentiated at 6-7 months but it was associated with a bilateral distribution at this young age whereas it turned into a clear left-hemispheric activation after 12 months of age (Minagawa-Kawai, Mori, Naoi, & Kojima, 2007).

The bilateral recruitment can be seen as compensatory mechanism often also found in patients suffering from specific language impairments (Rinker et al., 2007) or dyslexia (Zhang, Whitfield-Gabrieli, Christodoulou, & Gabrieli, 2013). It was furthermore suggested that a unilateral lateralization increases computational efficiency as duplication of functions in two hemispheres would claim too many resources which are not necessary and furthermore interhemispheric interaction would need too much time potentially slowing complex processing (Corballis, 2009; Ringo, Doty, Demeter, & Simard, 1994).

These studies show that it is still not clear if hemispheric lateralization is already present at birth or whether it develops later on. A potential influence of the duration of the stimulus (sentences versus isolated words) could provide an important cue impacting lateralization in young infants as more linguistic context might increase attention to the linguistic input and thus facilitate language processing. This issue is described in more detail in the first paper of this habilitation treatise.

3.3 Electrophysiological correlates of word learning

3.3.1 Electrophysiology of language in the adult brain

Several ERP components were identified for the differential linguistic functions. I will focus on the N400 as most relevant during word learning. In adults, the N400 component was found at the sentential as well as the word level. The N400 is a negative shift occurring around 400 ms post-stimulus onset and exhibiting a centro-parietal distribution (for reviews on the N400 please refer to Kutas & Federmeier, 2011; Lau, Phillips, & Poeppel, 2008).

In sentences, larger N400 amplitudes are elicited when one word does not match the semantic content of the sentence thus resembling detection of semantically incorrect contexts (Friederici, Pfeifer, & Hahne, 1993; Kutas & Hillyard, 1980). But a similar modulation was also observed when the word is not only semantically incorrect but also less plausible but potentially possible in this context (Federmeier & Kutas, 1999).

At the word level, increased amplitudes were found for pseudowords when compared to real words as they need more processing resources for performing lexico-semantic categorization (Bentin, McCarthy, & Wood, 1985; Chwilla, Brown, & Hagoort, 1995; Soares, Collet, & Duclaux, 1991). The increased N400 thus indicates a more laborious search for a potential candidate in the lexicon. Analogously, a larger N400 was found for low frequent words compared to high frequent ones or for words presented for the first time compared to repeatedly presented words (Kutas & Federmeier, 2000).

Phonotactics is a phonological cue impacting lexical search, thus an N400 modulation is also expected. Indeed, one study investigated the electrophysiological correlates of phonotactic processing in adults (Friedrich & Friederici, 2005). Real words, pseudowords which corresponded to phonotactic rules of the subjects' native language, and pseudowords which did not correspond to the native language (i.e., non-native pseudowords) were acoustically presented to adult and infants subjects together with the visual presentation of pictures of real objects. Results in adults showed an increased N400 for native pseudowords compared to non-native rules.

At first glance, this seems quite surprising as non-native pseudowords would be expected to be more difficult to be processed than native ones and thus would elicit a larger N400. But because non-native regularities are not relevant for the subjects' already established native language, at least when not integrated in an obvious learning context, these rules are discarded and pseudowords treated as nonwords. Thus, a lexical search is not initiated at all and the amplitude of the N400 is reduced.

Due to the very restricted number of electrophysiological studies in adults focusing on phonotactic processing, it is not clear whether phonotactic rules are extracted and such an N400 modulation also occurs when stimuli are presented only passively without any semantic context or whether a lexico-semantic context is required to trigger such processing.

Word learning during adulthood also occurs especially when learning a foreign language. An EEG study investigated the impact of a naturalistic classroom instruction of French as a foreign language (McLaughlin, Osterhout, & Kim, 2004). A learning subjects' group was compared to a group of subjects measured at the same time points but without receiving any instruction. During the EEG experiment prime-target word or pseudoword pairs were presented. Real words were subdivided in related and unrelated pairs. Findings of the learning group showed an increase in N400 for pseudowords after only 14 hours of classroom instruction suggesting very fast neuronal changes associated with successful foreign language learning.

Other studies investigated more restricted learning settings focusing on a specific learning setting such as associative learning. In a magneto-encephalographic (MEG) study the magnetic counterpart of the N400 was investigated. Subjects had to learn pseudowords and real words associated with pictures of real objects (Dobel, Junghöfer, et al., 2009). Subjects performed the training for five consecutive days (~20 min á day). Training consisted in the visual presentation of an object and a word after which subjects had to press a button whether they intuitively thought that they belonged together or not. No feedback was provided. Thus, subjects had to learn the correct associations from the mere repetitive correct combinations intermixed with random combinations which were presented less frequently. Results showed a larger N400m for pseudowords compared to real words before training. The N400m amplitude with respect to pseudowords reduced after training and approximated the amplitude of real words. Authors interpret these modulations as reflecting a successful access to existing conceptual representations in the lexicon for newly learned words (Dobel, Junghöfer, et al., 2009). It should be noted that this study used novel words which conformed to phonotactic rules of the subjects' native language. In a different study, a similar training was applied to learning of pseudowords which contained non-native phonemes (Dobel, Lagemann, & Zwitserlood, 2009). Interestingly, the N400m increased after training indicating that they lost the nonword status and the integration in the lexicon started.

These studies again show that the N400 modulation is not linear but undergoes an inverted U-shaped pattern being reduced when lexical or prelexical information is completely unfamiliar as for nonword and afterwards increases as encoding processes establish and pseudowords get integrated into the lexicon. When, however the access to the lexicon is eased because for example the words is learned and consolidated (as this is the case for real words) the N400 amplitude reduces again.

Lexico-semantic processing by means of the N400 was also investigated in different types of aphasic patients. Results suggest reduced, delayed, or absent N400 effects as an indication of impaired lexico-semantic abilities at least partially interwoven with phonological impairments (Hurley et al., 2009; Kawohl et al., 2010; Kojima & Kaga, 2003; Robson, Pilkington, Evans, DeLuca, & Keidel, 2017). Furthermore, the topographic distribution of the N400 in aphasic patients was found to differ from healthy controls in that it shows to recruit more right hemispheric resources but this tendency can also be modified by intensive training (Wilson et al., 2012). These changes nicely reflect massive neuroplastic changes occurring after a brain lesion.

3.3.2 Electrophysiology of language in the developing brain

The N400 component as an index for lexico-semantic processing was found to be subject to several changes during language development. A reliable N400 effect resembling adult semantic processing at the sentence level (i.e., comparing semantically correct versus incorrect sentences) was found between 6 and 13 years (Hahne, Eckstein, & Friederici, 2004). However, latencies of the N400 were found to get shorter and amplitudes become more negative with increasing age suggesting developmental changes.

The picture becomes more complex when looking at lexico-semantic development during the first years of life. Several precursor components of the N400 were found and discussed. In the following the most relevant findings will be outlined.

During very initial word learning a new word form has to be learned. This means that it has to be encoded in memory (i.e., the mental lexicon). This can be achieved by means of different learning scenarios such as through mere passive exposure but also by creating an associative link between a word form and an object.

ERP studies investigating mere exposure consistently showed increases in frontally distributed negativities between 100 and 1000 ms (also referred to as N200-500) with increasing exposure.

ERP studies in 10- and 7-month-old infants (Kooijman, Hagoort, & Cutler, 2005; Kooijman, Junge, Johnson, Hagoort, & Cutler, 2013) performed a familiarization phase in which low frequency words were acoustically repeated 10 times. Afterwards, the test phase started in which these newly familiarized words were integrated in sentences and compared to sentences containing low frequency words not familiarized before. ERP findings showed an increase in negativity over frontal regions with increasing exposure, both during the familiarization phase as well as during the test phase. Interestingly, the authors ascertained that the ERP difference between familiar and unfamiliar words presented during the test phase showed a negative polarity in 10-month-olds (Kooijman et al., 2005) while younger 7-month-olds showed a positive polarity (Kooijman et al., 2013). Inverted polarities in young infants were often found to reflect immature processing steps (e.g., Friedrich, Herold, & Friederici, 2009; He, Hotson, & Trainor, 2009; Mueller, Friederici, & Männel, 2012). Support for such an interpretation comes also from an additional analyses in individual subjects performed by Kooijman et al. (2013). They grouped 7-month-old subjects with respect to whether they showed a positive or negative polarity and compared the two groups with respect to the performance in several language tests at 3 years of age. They could show that a positivity at 7 months predicted worse performance at 3 years.

A similar pattern of increased negativities as a function of familiarity was also found in older infants around 20 months (Mills, Coffey-Corina, & Neville, 1993) suggesting that learning by mere exposure is crucial during the first two years of life. Such a mechanism, thus, reflects the encoding of word forms in memory. This shows that encoding is indispensable during initial word learning because only what is anchored in memory can also be reliable accessed when needed.

Language learning during infancy can also occur in an associative learning context such as word-object combinations. ERP studies found both modulations in a frontally distributed negativity as well as with respect to the centro-parietal N400 component.

The frontal negativity was found to be increased whenever learning in the sense of encoding in memory of repeatedly presented novel word/pseudoword - object/pseudoobject combinations occurred. Such an effect was found in 19-20-month-old children (Mills, Plunkett, Prat, & Schafer, 2005; Torkildsen et al., 2009), in 14-month-olds (Friedrich & Friederici, 2008), in 12-month-olds (Friedrich & Friederici, 2005), in 6-month-olds (Friedrich & Friederici, 2011), and also in 3-month-olds (Friedrich & Friederici, 2017). This effect thus reflects the successful association between a word form and an object. In particular, a similar effect was also found in 12-month-old infants being exposed to phonotactically native and non-native pseudowords (Friedrich & Friederici, 2005). An increase in negativity was here observed for pseudowords conforming to native phonotactic rules suggesting that also pre-established linguistic knowledge developed during several months of life plays a crucial role for learning mechanisms. The frontal negativity reflecting the establishment of a successful associative link was shown to emerge very fast, after only few repetitions. Whereas in 6-month-olds this association is still present the day after the learning phase suggesting some instantiation in long-term memory (Friedrich & Friederici, 2011), in 3-month-old the associative link seems to be retained only on a short-term basis (Friedrich & Friederici, 2017).

Modulations with respect to the N400 component were mostly found in paradigms congruously or incongruously pairing words/previously learned pseudowords with objects/pseudoobjects. The N400 in these experiments consistently showed an adult-like N400 effect reflected in reducing amplitudes for congruous compared to incongruous combinations. Such an effect suggests a semantic priming or incongruity effect due to the eased access to the lexicon for combinations already stored in memory. This effect was found in 19-20-month-old children (Friedrich & Friederici, 2005; Torkildsen et al., 2008, 2009; Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007), in 14-month-olds (Friedrich & Friederici, 2008), in 6-month-olds (Friedrich & Friederici, 2011), but not in 3-month-olds (Friedrich & Friederici, 2017). Interestingly, however, while the establishment of an N400 effect can be achieved quite quickly, retention in long-term memory of these semantic associations (partially mediated through overnight consolidation) was found only in 14-month-olds (Friedrich & Friederici, 2008) but not in 6-month-olds (Friedrich & Friederici, 2011) (for a recent review on the impact of sleep on memory consolidation please refer to Friedrich, Wilhelm, Mölle, Born, & Friederici, in press).

4. Research questions

In our globalized world, it is very important to be able to communicate in different languages in professional, private, and societal life. But what helps us become highly proficient in a foreign language? In the present habilitation treatise I put under investigation which neuronal changes occur when confronted with a non-native language compared to the native language, how the brain learns new words through different word learning strategies, whether neuroplastic mechanisms of word learning differ during infancy, childhood, adulthood, and after a brain lesion, and which role bilingualism plays when learning words of a new language.

One important linguistic feature relevant during word learning is phonotactics. Phonotactic rules describe the possible combinations of phonemes in a specific language (Trask, 1996). They are phonological cues impacting lexical access by aiding segmentation of the acoustic speech stream into smaller units. These units represent the word forms which have to be learned. Once encoded in memory, they can be accessed from the lexicon. Because phonotactic cues play a crucial role during very initial language learning we compared the processing of native and non-native rules in 5 of the following experiments in infants, healthy adults, and patients having to re-acquire language after a brain lesion. In particular, we focused on how the brain differentiates between these rules, which brain areas are recruited, and how neuronal mechanisms change under different learning settings. After initial word learning, vocabulary still grows throughout childhood. More sophisticated aspects of word learning have to be learned. Around 5 years of age, for example the processing of adjectives was found to be quite challenging. Thus, in Experiment 6 we focused on learning new adjectives. Furthermore, the impact of bilingualism on learning new adjectives was analyzed as bilingualism is often associated with enhanced cognitive processing mechanisms due to the more variable linguistic environment and the necessity to switch between languages.

Learning can be achieved through different word learning strategies, such as mere passive exposure, semantic-associative training, or pragmatic cues. The former is operationalized by repetitive passive listening exposure to the to-be-learned stimuli. Semantic-associative trainings combine the acoustic presentation of pseudowords with the visual presentation of pseudoobjects. Furthermore, the impact of hand gestures as pragmatic cues, highlighting the property or the name of the whole pseudoobject, on word learning was investigated in children.

In the following the research questions will be described:

1. ***Do adults and infants recruit the same brain areas and show a similar lateralization for language? (Article 1)***

Since emerging of neuroscientific methods, researchers try to explore which brain areas support various linguistic functions. Several methods have been used such as electro- (EEG) or magnetoencephalography (MEG), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI). With increasing findings, the complexity of the language network became always more evident. The simplistic view that one brain region supports one specific function was soon rejected when asserting that different functions activated the same brain area and one experimental manipulation showed recruitment of different brain areas. Thus, the brain can be considered a network, and also language functions recruit a highly complex brain network.

The language network was located around the sylvian fissure with inferior frontal, superior and middle temporal, as well as parietal brain areas playing the major role during language processing (Binder, 2017; Hickok & Poeppel, 2015; Skeide & Friederici, 2016; Vigneau et al., 2006).

Because the brain is not static and already complete at birth but undergoes several developmental trajectories, studying differences between the adult and developing brain became increasingly important. In the last decades, also language research focused on developmental aspects. Experimental designs using neuroscientific methods were adapted to investigate the processing steps in the developing brain. Because fMRI with its excellent spatial resolution is however not easy applicable in young infants and children because of the unnatural setting in the narrow scanner tube surrounded by a loud acoustic noise necessitating hearing protection and requiring the subject under investigation to lie as still as possible, other methodologies had to be established. One such infant-compatible neuroscientific methodology is functional near-infrared spectroscopy (fNIRS). fNIRS is well tolerated by infants as it does not require a fixed scanner but the infant can sit on the parent's lap wearing a soft cap in which light emitters and detectors measuring brain activity are integrated. Furthermore, fNIRS relies on the same physiological (i.e., vascular) basis as fMRI (for details regarding the method of fNIRS please refer to Section 3.1.2). However, spatial resolution is not as high as in fMRI but better than in EEG. Thus, a good spatial resolution can be achieved with fNIRS. Furthermore, it does not generate any acoustic noise, thus it is especially suitable for assessing fine-grained acoustic processing.

One important question in language acquisition research is whether an adult-like hemispheric lateralization, manifesting in segmental linguistic information or fast acoustic variations being predominantly processed in the left hemisphere and suprasegmental slower information in the right hemisphere (Friederici & Alter, 2004; Poeppel et al., 2008), is already established at birth or whether it develops with incremental improvements in language use, most likely mediated by brain maturation. Inconsistent results were found in literature. Some studies showed a hemispheric lateralization already at birth or during the first months of life (Dehaene-Lambertz et al., 2002; Homae et al., 2006; Peña et al., 2003; Telkemeyer et al., 2009) whereas others were not able to attest a clear lateralization during the first year of life (Minagawa-Kawai et al., 2007; Sato et al., 2003 cited in Minagawa-Kawai et al., 2008; Sato, Sogabe, & Mazuka, 2010).

The need for a systematic overview on the recruitment of brain areas and associated hemispheric lateralization in adulthood but more importantly during infancy and childhood became apparent. Thus, in Article 1 we tried to systematize existing fNIRS studies on word and sentence processing in infants, children, and adults. We especially focused on which driving forces may explain inconsistent findings with respect to the presence of hemispheric lateralization in young infants and hypothesize that the amount of linguistic context (for example sentences versus words in isolation) may play a crucial role in increasing attention to the stimuli and thus facilitate processing which in turn might lead to a more efficient adult-like lateralization.

Especially findings reviewed in Article 1 with respect to word processing provide the basis for the research questions addressed in Experiments 1, 2, and 5.

2. *How does the adult brain process native and non-native phonotactic rules under passive listening conditions? (Article 2, Experiment 1)*

Distinguishing the native language from a non-native language is one important step during infancy which has to be successfully mastered during healthy language acquisition. This increase in sensitivity for features of the native language and a decrease in sensitivity for features not relevant for the native language are referred to as *perceptual narrowing* (Kuhl et al., 2008; Werker & Tees, 1984). In monolingual infants perceptual narrowing takes place during the first year of life. If such a change in sensitivity does not occur during this period later language impairments may arise (Kuhl et al., 2008). Perceptual narrowing was found especially regarding phoneme discrimination. In Article 2 we investigated phonotactics, the combinational rules of different phonemes in a language (Trask, 1996). In monolingual adults, we clearly expected that perceptual narrowing has been already successfully taken place during infancy, thus the adult brain should be able to differentiate between native and non-native phonotactic rules.

In Experiment 1 we were especially interested in the neuronal underpinnings of phonotactic processing as hardly any neuroscientific study investigated this specific linguistic feature. Phonotactics is particularly interesting to investigate due to its intermediate role between phonology and semantics. It is phonological in nature but supports lexical processing and thus plays a role during word learning. Before investigating neuroplasticity elicited through different language learning strategies in Experiments 3, 4, and 5, we first wanted to determine which neuronal processing mechanisms are at the basis of phonotactic processing. To accomplish this goal we simultaneously assessed electrophysiological correlates by means of EEG in order to track fast dynamic mechanisms and vascular responses by means of fNIRS in order to identify the neuronal network supporting phonotactic processing.

With respect to electrophysiological correlates only one ERP study compared pseudowords conforming to native phonotactic rules and non-native rules in adults (Friedrich & Friederici, 2005). The authors integrated not only pseudowords but also real words in their experimental design and applied a semantic-associative task in which not only the acoustic stimuli but also pictures were presented at the same time. Event-related brain potentials (ERPs) revealed an increased N400 component for native phonotactic rules compared to non-native ones suggesting that for native regularities a search for possible candidates in the lexicon is triggered because the rules are familiar to the subjects whereas non-native regularities are discarded because they do not belong to the subjects' native language repertoire (Kutas & Federmeier, 2011). In Experiment 1 we follow this line of reasoning, however, we specifically asked whether such a differential processing can also be elicited without a semantic context, thus being processed implicitly. We presented phonotactically native and non-native pseudowords only acoustically without any additional visual input. It is known that directing the attention to experimental stimuli is much more necessary in adult participants than infants. Some studies investigating preattentive processing of non-adjacent dependencies (i.e., also rule-based processing) report no neuronal differentiation in adult participants when no task was provided (Mueller et al., 2012). If phonotactic rules can be processed implicitly in adults we expect a larger N400 for native compared to non-native rules.

A second aspect referring to whether phonotactics is susceptible to attentional influences was introduced in the experiment by manipulating the speech mode of pseudowords. All native and non-native pseudowords were presented in adult-directed speech (ADS) as well as infant-directed speech (IDS). IDS contains more prosodic aspects such as a higher intonation, a longer vowel duration, and a greater clarity in pronunciation (Soderstrom, 2007) and was found to help infants during language acquisition probably due to the direction of attention to relevant stimuli (Cooper & Aslin, 1994; Pegg et al., 1992; Saffran et al., 1996; Weisleder & Fernald, 2013). If adults process phonotactic rules implicitly, thus without a special direction of attention to the relevant linguistic features, then we also assume that IDS should not be processed differentially to ADS.

With respect to brain areas recruited specifically for phonotactic processing no neuroimaging study at the time of study execution was published. Thus, Experiment 1 was highly innovative with respect to the network underlying phonotactic processing. We expected a fronto-temporal network to be involved. But due to the intermediate position of phonotactics between phonology and semantics (Binder et al., 1997; Binder, 2017; Hickok & Poeppel, 2007; Rissman et al., 2003; Skeide & Friederici, 2016; Vigneau et al., 2006) we aimed at exploring whether regions supporting phonological processing (such as IFG and posterior STG or parietal areas) or semantic processing (such as anterior STG and MTG) were predominantly recruited during phonotactic processing. In accordance with the *Dynamic Dual Pathway model* (Friederici & Alter, 2004) postulating a left-hemispheric recruitment for segmental linguistic information including phonology and semantics we expected a left-hemispheric network to underlie phonotactic processing.

3. How does a lesioned brain process language-specific and universal linguistic features? (Article 3, Experiment 2)

Language consists of features which are specific to a given language (e.g., the word order of sentences). However, some general aspects such as the fact that sentences contain phrases or that words consist of single phonemes, are universal characteristics to all languages of the world. Such an idea was introduced in the *Universal Grammar* as well as *Principle and Parameter Theory* by Noam Chomsky (Chomsky, 1976; Chomsky, 1981). This dichotomy is important because both systems have to function properly in order to enable the powerful language acquisition capacity. But what happens in the brain when a lesion (e.g., a stroke) occurs in language-related areas? This is one of the questions addressed in Experiment 2. In particular, pseudowords corresponding to native and non-native phonotactics were acoustically presented as a language-specific constraint. The contrast of pseudowords played in a reversed manner (i.e., digitally reversed audio files) compared to a forward manner was selected as a universal constraint of "phonotactic well-formedness" as sounds played in a reversed fashion in general are dispreferred due to the violation of prelexical structure. By using reversed speech we could however control for acoustic characteristics as the same frequencies as in pseudowords played forward were contained. Healthy control subjects as well as patients suffering from a left-hemispheric brain lesion including language-related brain areas underwent an ERP study in which phonotactically native and non-native pseudowords played in a forward and reversed fashion were acoustically presented. For healthy controls, we expected a larger N400 for phonotactically native pseudowords compared to non-native ones (Rossi et al., 2011).

With respect to the universally preferred versus dispreferred items we also expected a larger N400 component for preferred items as they may be expected to trigger lexico-semantic processes to a larger extent than dispreferred sequences of phonemes (Kutas & Federmeier, 2011; Lau et al., 2008). We expected differential N400 modulations, reflected in a reduced, delayed, or absent N400, in patients due to the massive neuroplastic changes and reorganization of the brain after lesions (Hartje & Poeck, 2002; Hurley et al., 2009; Kawohl et al., 2010; Kojima & Kaga, 2003; Robson et al., 2017; Saur et al., 2006).

The second aim of this study was to identify the brain regions supporting language-specific and universal phonotactic processing by looking at the lesion in patients and correlating the lesion location either with behavioral performance on phonological, lexical, and semantic neuropsychological tests or with the ERP modulation during the EEG experiment. The latter EEG-lesion analysis represents an innovative extension of the voxel-based lesion-symptom mapping (Bates et al., 2003) and was expected to provide important new findings on the neuronal network involved during language. A high-resolution scan was acquired in each patient by means of the magnetic resonance imaging and lesions were delineated manually in the three-dimensional space classifying each voxel as lesioned or not. Lesioned regions were expected to correlate with worse behavioral performance and less differential ERP modulations between the two language-specific and universal constraints. In particular, the left IFG was found to be involved during processing of phonotactic frequency (Vaden, Piquado, & Hickok, 2011) and the posterior STG as well as MTG and inferior temporal gyrus (ITG) were found to contribute in differentiating between native and non-native phonotactic rules (Gow & Nied, 2014).

4. Can adults learn new native and non-native words through mere passive exposure? (Article 4, Experiment 3)

In Experiment 1 we could show that native and non-native linguistic rules can successfully and fast be differentiated by the adult brain (Rossi et al., 2011). In the EEG, an N400 modulation was found suggesting a successful lexical search for native phonotactic rules (indexed by an increase in N400) and a deselection of non-native rules which are not relevant for the native language (indexed by a decrease in N400). It should be noted that the N400 does not show a linear amplitude modulation but rather an inverted U-shaped path. It shows reduced amplitudes if the lexical or prelexical information is completely unfamiliar but also when information is already stored and consolidated in memory and thus access is facilitated. If, however, the information is demanding and necessitates more resources because it is currently in the learning process or because it is unexpected than an increase in N400 amplitude was found (Bentin et al., 1985; Chwilla et al., 1995; Friedrich & Friederici, 2005; Rossi et al., 2011; Soares et al., 1991).

Thus, we focus on N400 modulations also in the present experiment to track fast dynamic changes during learning. In particular, we explored whether repetitive passive listening exposure to new words can shape neuronal processing of native and non-native rules in adults. Learning a foreign language during adulthood is more demanding as during childhood. However, studies showed that very similar neuronal processing mechanisms as used during first language processing can be achieved when a high proficiency level was attained (Rossi et al., 2006). In our society, we often have to learn a new foreign language during adulthood, for professional or private reasons. But how flexible is our brain in accomplishing this challenging task?

In Experiment 3 we focused on the very initial word learning. Subjects performed a pretest, training, and posttest. During training subjects had to passively listen to pseudowords corresponding to native and non-native phonotactic rules. These trained items were compared during pre- and posttest with untrained items. In order to investigate short-term and longer-lasting neuronal changes pretest, training, and posttest were repeated on three consecutive days. Experiment 1 revealed an implicit processing of phonotactic rules and an impact of mere exposure on newly learned regularities (Citron, Oberecker, Friederici, & Mueller, 2011). Thus, we also expected electrophysiological modulations induced by a mere acoustic exposure without any semantic context. Native rules were expected to be less impacted by passive listening exposure or to show reductions in N400 amplitude as familiar rules get more automatized with increasing exposure. For non-native rules two different hypotheses were formulated: (1) If the N400 gets larger with increasing acoustic exposure then a process of encoding in the lexicon may be triggered also without a semantic context. (2) If, however, the N400 decreases over time, this speaks for a better deselection of linguistic rules not relevant for the native language. In such a case, acoustic exposure would not suffice to integrate new foreign words in the lexicon.

Because successful learning consists not only in learning a specific linguistic rule but also in the ability to generalize this rule to other items, it was of particular interest whether for native and/or non-native regularities generalization effects to untrained items might occur.

5. Can adults learn new native and non-native words through semantic categorization? (Article 4, Experiment 4)

Experiment 4 is analogously designed as Experiment 3 but the training differs. In order to investigate a potential impact of a semantic context on neuronal processing of native and non-native rules a semantic categorization task was introduced. During this task, subjects had to categorize native and non-native pseudowords according to an arbitrary category A or B. After each categorization performed by button press, subjects received a visual feedback whether their response was correct or not. Thus, a protosemantic context was introduced. With respect to the N400 modulation, for native rules we again expected no modulation or a reduction in amplitude due to the facilitated access in the lexicon with increasing exposure. For non-native rules, increases in N400 amplitude were expected due to the protosemantic context triggering the integration of new linguistic rules in the lexicon. Such a hypothesis is supported by studies showing an increase in strength of the magnetic counterpart of the N400 assessed by means of MEG when pseudowords containing non-native phonemes were learned in a semantic context with real objects (Dobel, Lagemann, et al., 2009). Whereas Dobel, Lagemann et al. (2009), however, investigate classical second language acquisition in which the object is known and the corresponding name of the object is familiar in the native language and has now be learned in the foreign language, our semantic categorization training provides a very limited semantic context consisting of only two arbitrary categories A and B. If similar results as in Dobel, Lagemann et al. (2009) can be found for non-native rules this would suggest the presence of very basal learning mechanisms in adults, probably resembling those present in infants who have to learn both the word form as well as the object and successfully associate them together in order to allow for integration into the lexicon.

6. *How does a semantic-associative training impact neuronal processing of native and non-native rules in 6-month-old infants? (Article 5, Experiment 5)*

Fast mapping during initial language acquisition in infancy is a very powerful learning mechanism. Infants learn to associate new word forms to the corresponding objects and can thus encode the single words and objects but also the association in memory (Carey & Bartlett, 1978). Word learning through fast mapping was found to be facilitated for pseudowords following linguistic rules of the native language in infants around 14-19 months (Graf Estes, 2014; Graf Estes & Bowen, 2013; Graf Estes et al., 2011).

In Experiment 5 we investigated the impact of a semantic-associative training on neuronal processing of native and non-native phonotactic rules in 6-month-old infants. During infancy, linguistic rules are subject to *perceptual narrowing*, that is an increase in sensitivity for native rules and a decrease in sensitivity for non-native rules. Behavioral studies showed that perceptual narrowing takes place around the end of the first year of life (Friederici & Wessels, 1993; Jusczyk et al., 1993; Kuhl et al., 2008; Werker & Tees, 1984). Neuroscientific studies, however, showed that already at 4 months infants can differentiate between native and non-native stress patterns (Friederici, Friedrich, & Christophe, 2007). But because stress pattern is a prosodic aspect already perceivable during the last trimester of pregnancy in utero, the question arises whether phonotactic cues, which represent more fine-grained acoustic cues and thus are not perceivable in utero, show a similar developmental trajectory as found in Friederici et al. (2007). A recent study performed in our group shows that 6-month-olds can successfully differentiate between native and non-native phonotactic rules (Rossi et al., in prep.).

The design of the present study resembles that of Experiment 3 and 4. It includes a pretest, training, and posttest on three consecutive days. Training, however, consisted in the repetitive presentation of phonotactically native and non-native pseudowords with picture of pseudoobjects. This association is organized according to the principle of *statistical learning*, that is, what is more frequently correctly combined is more likely to be learned (Aslin, 2017; Saffran et al., 1996). Accordingly, we presented correct pseudoword/pseudooject pairings six times interspersed with distracting random pairings.

In contrast to the adult experiments, pseudowords were spoken in infant-directed speech (IDS) as this is the most natural speech mode infants are used to listen to (Kuhl et al., 1997; Soderstrom, 2007). IDS increases attention to relevant speech stimuli and aids word learning even though it is not a necessary prerequisite (Schieffelin, 1979). Because IDS accentuates prosodic aspects it might be expected to elicit a stronger recruitment of the right hemisphere (Friederici & Alter, 2004).

Phonotactics in general aids speech segmentation and once single units are segmented the word form and afterwards the semantic word meaning can be learned. This represents a bottom-up process. However, acquired lexico-semantic knowledge can also foster statistical phonological learning and thus improve segmentation (Bortfeld, Morgan, Golinkoff, & Rathbun, 2005). Thus, phonotactics is also affected by top-down influences partially driven by domain-general mechanisms such as attention, memory, and general cognitive abilities. This top-down influence was in the focus of investigation in Experiment 5. We expected increases in negativities in the EEG as well as increases in activations in the fNIRS as a reflection of successful familiarization and thus memory encoding of newly learned items (Friedrich & Friederici, 2005, 2008, 2011, 2017, Kooijman et al., 2005, 2013, Mills et al., 1993, 2005; Torkildsen et al., 2009).

In particular, we were interested in whether learning effects differ for native and non-native phonotactic rules as attested in older infants (Graf Estes, 2014). If a differential impact of the training is found, this would imply that previous linguistic experience with the native language starts to restrict flexibility of learning new languages and thus resembles adult-like processing mechanisms (Rossi, Hartmüller, Vignotto, & Obrig, 2013). If, however, similar learning effect will be observed for native and non-native rules this would indicate a still available flexibility of the brain for learning all various kinds of new input. In such a case, perceptual narrowing would only less restrict the learning abilities of infant at this young age.

Long-term memory retention was found to be very fragile in young infants (Friedrich & Friederici, 2011, 2017). A recent study, however, could show a beneficial impact of sleep on memory retention (Friedrich et al., in press). By introducing a three-day training we were able to assess both learning effects establishing over a longer period and potential overnight consolidation effect.

The multi-methodological approach used in the present experiment combining electrophysiological and vascular methods allows assessing brain areas involved during early word learning processes with greater spatial precision. Especially lateralization in the developing brain can be an index for maturation (Minagawa-Kawai et al., 2007). It furthermore can indicate whether more linguistically oriented or more general acoustic processes guide the effects. At 6 months of age both more acoustically driven associative processes (usually reflected in frontally distributed negativities in the EEG) as well as more lexico-semantically oriented processes (usually reflected in an N400 component) after a certain period of training were found (Friedrich & Friederici, 2011). A stronger left-hemispheric recruitment would support more linguistically oriented mechanisms rather than domain-general learning abilities.

7. How do pragmatic cues impact word learning in monolingual and bilingual 5-year-old children? (Article 6, Experiment 6)

Word learning does not only occur during infancy but with increasing vocabulary also word learning strategies improve and adapt to more complex learning settings. Around 5 years of age children acquire adjectives describing the properties of objects. Findings revealed that this is a quite challenging task at this age (Holland et al., 2015; Perry et al., 2016). Furthermore, it was found that children use socio-pragmatic cues such as gaze, gestures, and other actions to infer which word-object association is intended by the speaker (Baldwin, 1993; Hansen & Markman, 2009; Kang & Tversky, 2016; Kobayashi, 1998; O'Connell et al., 2009; Paulus & Fikkert, 2014; Tomasello, 1988). Gestures during word learning, in particular, increase attention to the relevant stimuli and enhance retention in memory (Macedonia & Mueller, 2016; Muzzio et al., 2009; Nyberg et al., 2001).

In the present experiment we aimed at investigating the impact of gestures during challenging adjective learning. The topic is innovative per se in monolingual children but because bilingual subjects were found to show increased pragmatic skill beneficially enhancing the recognition of other's states (Colunga, Brojde, & Ahmed, 2012; Farhadian et al., 2010; Greenberg, Bellana, & Bialystok, 2013; Yow, 2015; Yow & Markman, 2011), we compared neuronal changes during learning between monolinguals and bilinguals 5-year-old children.

Participants underwent a gestural training in which pseudoobjects were visible on the screen. Either the property or the category of the pseudoobject were highlighted by either a stroking or pointing gesture while the new name of the property or category was repeatedly presented acoustically. The training was integrated in a pleasant computer video game suitable for children. During the learning phase functional near-infrared spectroscopy (fNIRS) was recorded in order to identify brain areas supporting word learning supported by socio-pragmatic cues.

The brain network underlying the identification of communicative intentions was found to include the superior temporal sulcus (STS), the superior parietal cortex, the temporal parietal junction (TPJ), and the prefrontal cortex (Enrici et al., 2010). Furthermore, the prefrontal cortex is involved in executive functions such as cognitive control, inhibition, and cognitive flexibility (Dajani & Uddin, 2015; Miyake et al., 2000; Niendam et al., 2012), found to be relevant during bilingual language processing as bilinguals have to switch between languages and inhibit one language when they currently use the other (Bialystok, Barac, Blaye, & Poulin-Dubois, 2010; Buchweitz & Prat, 2013). Thus, we expected an increased involvement in brain networks supporting the identification of communicative intents as well as the prefrontal cortex in bilingual compared to monolingual children if adult-like mechanisms are already operative in 5-year-old children.

5. Methods

The neuroscientific methods adopted in the different experiments were chosen as the most sensitive methods to address a specific research question. The methods adopted include the electroencephalography (EEG), the functional near-infrared spectroscopy (fNIRS), as well as an innovative extension of the voxel-based lesion symptom mapping (VBLSM) based on structural magnetic resonance imaging (MRI) scans (for details regarding the methods please refer to Section 3). In Experiment 1 and 5 the simultaneous application of EEG and fNIRS was used, whereas in Experiments 3 and 4 only EEG, in Experiment 6 only fNIRS was reported. Finally, in Experiment 2 a novel combination of EEG and voxel-based lesion mapping (VBLM) was applied. Each neuroscientific assessment was accompanied by behavioral measures (e.g., questionnaires, standardized tests, accuracy rates, and reaction times) (Table 5.1).

Table 5.1. Method combinations used in the single experiments and articles.

Article	Experiment	Aim	Subjects	EEG	fNIRS	MRI/ VBLM	Behav
1		Review of word and sentence processing		✓	✓		
2	**1**	Processing native and non-native phonotactics	healthy adults	✓	✓		
3	**2**	Language-specific and universal processing	healthy adults, patients	✓		✓	✓
4	**3**	Word learning through passive listening	healthy adults	✓			✓
4	**4**	Word learning through semantic categorization	healthy adults	✓			✓
5	**5**	Word learning through semantic-associative training	6-month-olds	✓	✓		
6	**6**	Learning adjectives through gestures	5-year-olds mono- and bilingual		✓		✓

6. Empirical Part

In order to address the above mentioned research questions six experiments were performed. In the following, these experiments as well as a review article will be discussed. I first present a brief summary of each article and afterwards a more detailed description of each article follows.

The first article (Rossi, Telkemeyer, Wartenburger, & Obrig, 2012) is a review article focusing on language processing in infants, children, and adults predominantly assessed by fNIRS or the simultaneous combination of EEG and fNIRS. The article focuses on phonological, lexical, semantic, syntactic, prosodic, and statistical aspects of word and sentence processing and emphasizes changes in hemispheric lateralization during language development. The overview and conclusions with respect to the dynamics of brain changes especially for word processing during adulthood as well as during early language acquisition provide the basis for Experiments 1, 2, and 5.

Experiment 1 (Rossi, Jürgenson, Hanulikova, Telkemeyer, Wartenburger, & Obrig, 2011) provides the basis for the subsequent Experiments 2-5 in that it investigates the electrophysiological and vascular correlates of processing native and non-native phonotactic rules either with normal or exaggerated prosody (adult- versus infant-directed speech) in healthy monolingual adults without any specific learning context. EEG and fNIRS results provide evidence for a differential processing of phonotactic rules, irrespective of the prosodic manipulation. The EEG shows up in an N400 component resembling lexical processing whereas fNIRS results additionally provide evidence for a clear left-hemispheric fronto-temporal network underlying these processes.

Experiment 2 (Obrig, Mentzel, & Rossi, 2016) pursued two aims: (1) investigate electrophysiological modulations concerning universal versus language-specific regularities comparing patients affected by a left hemispheric brain lesion to age-, sex-, and education-matched healthy controls and (2) identify underlying brain areas. Universal constraints were operationalized by contrasting the acoustic presentation of naturally spoken pseudowords (i.e., forward) to digitally reversed pseudowords (i.e., reversed). Language-specific constraints consisted in phonotactically native versus non-native pseudowords. For identifying involved brain areas a voxel-based lesion-behavior and a novel voxel-based lesion-EEG correlation approach was used for patients. EEG results showed similar differences between native and non-native phonotactics in patients and controls as well as a clear differentiation between forward and reversed pseudowords, again quite similar in both groups. Brain regions supporting language-specific ERP modulations correlated with the middle to anterior portion of the middle and superior temporal gyrus, whereas ERP differences concerning universal differentiation projected to inferior and posterior parietal areas including the angular and supramarginal gyrus. These findings indicate a clear separation between a ventral and a dorsal stream, the former providing a language-specific link between phonological and lexical processing and the latter acting on universal phonological preference.

Experiment 3 (Rossi, Hartmüller, Vignotto, & Obrig, 2013) investigated the neuronal temporal dynamics in particular of the N400 component with respect to passive acoustic repetitive exposure over three consecutive days to native and non-native phonotactic rules in healthy monolingual adults. Especially non-native rule processing was in the focus of investigation in order to see whether monolingual adults are still capable of acquiring new foreign linguistic rules in a very short learning period over three days. Results showed a decrease in N400 with increasing passive listening exposure suggesting a successful deselection of rules which do not belong to the subjects' native language.

Experiment 4 (Rossi, Hartmüller, Vignotto, & Obrig, 2013) was similarly designed as Experiment 3 but focused on N400 changes when repetitive exposure consisted in a categorization task in which healthy monolingual adult subjects had to learn (by immediately provided feedback) to classify pseudowords of different native and non-native phonotactic rules to two arbitrarily defined categories (A or B). Thus, the task had no relation to phonotactic legality but introduced a protosemantic training context resembling an arbitrary mapping between a word's lexical form and its meaning. With respect to new non-native rules results show an abolishment of the decrease in N400 observed for passive listening and even an increase in N400 suggesting an attempt to integrate these foreign rules into the phonotactic repertoire. Intriguingly, this happens in a very short period over three consecutive days and in a protosemantic context pointing to arbitrary rule learning and not directly providing an associative learning context for example between a new word and a semantically related object.

Experiment 5 (Obrig, Mock, Stephan, Richter, Vignotto, & Rossi, 2017) investigated the impact of a semantic associative word learning context on processing native and non-native phonotactic rules in 6-month-old monolingual infants. Infants underwent a pretest, training, and posttest while electrophysiological and vascular changes were simultaneously monitored by means of EEG and fNIRS. In order to investigate immediate training effects as well as longer-lasting learning effects infants were assessed on three consecutive days. The semantic training consisted in the repetitive combination of phonotactically native and non-native pseudowords with pictures of pseudoobjects. EEG and fNIRS results showed stronger short-term (from pre- to posttests) than long-term (over the three learning days) training-induced effects. Furthermore, trained and untrained items were similarly affected by the learning effects suggesting generalization mechanisms. Finally, even though 6-month-olds differentiate between native and non-native phonotactic regularities, the impact of the semantic training was quite similar for native and non-native rules. These findings suggest that infants at this young age are not subject to strong influences arising from previous linguistic knowledge and are still open to learn new linguistic rules within an associative learning context. With respect to hemispheric lateralization a predominantly bilateral distribution was observable. Only for the increase in activation from pre- to posttest a stronger left-hemispheric dominance was present suggesting linguistic rather than domain-general familiarization effects at the basis of these modulations.

Experiment 6 (Groba, De Houwer, Mehnert, Rossi, & Obrig, 2017) aimed at investigating behavioral and neuronal changes in German-Spanish bilingual 5-year-old children having to learn novel adjectives by means of a pragmatic cue training. Learning adjectives represents a quite challenging task for children and has been rarely investigated in bilingual children. The training consisted in a hand gesture either highlighting the property or the category of the pseudoobject which was associated to a novel word. Afterwards, children had to select the correct pseudoobject either matching in property or category. Bilingual children underwent the training in both German and Spanish. Results showed no differential processing at the behavioral level. fNIRS results, however, demonstrated an increased activation in the right temporal cortex including the posterior part of the superior temporal sulcus (STS) for bilinguals compared to monolinguals. STS was found in adults to play a role during understanding gestural and sociolinguistic information and a reduced activation was found in children with autism spectrum disorder suggesting impaired pragmatic skills. Results of this study, thus, provide first evidence that the right STS also plays an important role in the context of bilingualism in young children.

6.1 Do adults and infants recruit the same brain areas and show a similar lateralization for language?

Rossi, S., Telkemeyer, S., Wartenburger, I. & Obrig, H. (2012). Shedding light on words and sentences: Near-infrared spectroscopy in language research. *Brain & Language, 121,* 152-163.

The here presented review article focused on language processing in infants, children, and adults predominantly using solely functional near-infrared spectroscopy (fNIRS) or by simultaneously applying the electroencephalography (EEG) and fNIRS. Many studies on language processing used EEG as method which is plausible due to its excellent temporal resolution in the range of milliseconds highly relevant for capturing fast occurring linguistic processing steps. EEG, however, is equipped with a low spatial resolution often neither being able to reliably identify hemispheric differences. This deficit relies on the inverse problem of source localization, according to which the brain areas generating the signal observed on the scalp are not directly determinable (Wendel et al., 2009). Thus, the need for complementary methods possessing a better spatial resolution emerged. Even though a better spatial resolution can be reached by magneto-encephalography (MEG), magnetic resonance imaging (MRI), and positron emission tomography (PET) they create highly unnatural situations by fixed apparatuses. Furthermore, movement restrictions and loud scanner noise in some of these methods lower the suitability for acoustic language studies in infants, children, and patients. fNIRS can overcome at least some of these caveats allowing a quite natural experimental setting in which infants, children, or patients can sit on a comfortable chair, on the parents' lap, or even lie in the bed and providing a silent environment allowing for fine-grained acoustic stimulation experiments. fNIRS is an optical method assessing vascular changes following neural activation by the application of near-infrared light. The physiological principle at the basis of fNIRS is neurovascular coupling (for details on this method please refer to Section 3.1.2). Due to the specific absorption spectra of near-infrared light in biological tissues, the concentration of oxygenated (HbO) and deoxygenated (HbR) hemoglobin can be calculated. Both increases in HbO as well as decreases in HbR are indicators of increased neuronal activation in the underlying brain areas. It should be underlined that spatial resolution is only rough compared to fMRI and PET reaching only centimeters. Also the depth of measurement is limited to 2-3 cm below the scalp, thus only allowing the measurement of cortical areas. Nevertheless it has a better spatial resolution than EEG and thus it has predominantly used for assessing lateralization during language development. A major advantage of fNIRS is that the assessment does not interfere with electrophysiological signals (as fMRI does). This allows an easy combination of EEG and fNIRS, for example mounted in a commercially available EEG cap. This is especially beneficial when applied in highly selective subject cohorts such as infants or patients.

The article is divided in two main foci, fNIRS studies on word and sentence processing providing an overview concering all relevant linguistic features (phonological, lexical, semantic, syntactic, prosodic, and statistical aspects) necessary during first language development. Even though the review focuses on neuronal processing mechanisms (especially on hemispheric lateralization) during infancy also findings in adult subjects were discussed. Due to the emerging co-registration of EEG and fNIRS, also combinatory results were included in the article.

The overview and conclusions with respect to the dynamics of brain changes especially for word processing during adulthood and early language acquisition provide the basis for Experiments 1, 2, and 5.

With respect to word processing especially phonological and prosodic manipulations were reviewed as these are the most important linguistic aspects during initial language acquisition aiding segmentation of the acoustic speech stream into single units (McQueen, 2007; Sebastián-Gallés, 2007). fNIRS studies reliably found a stronger left-hemispheric network for phonological contrasts and a predominantly right-hemispheric network recruited for processing of prosodic contrasts. This pattern was visible in adults (Furuya & Mori, 2003 cited in Minagawa-Kawai, Mori, Hebden, & Dupoux, 2008; Rossi et al., 2011) and infants in the second year of life (Sato et al., 2003 cited in Minagawa-Kawai et al., 2008). During the early prelingual phase during the first year of life differentiation mechanisms between the manipulated conditions were partially observable, however, they still recruited bilateral brain areas (Minagawa-Kawai, Mori, Naoi, & Kojima, 2007; Sato et al., 2003 cited in Minagawa-Kawai et al., 2008; Sato, Sogabe, & Mazuka, 2010). Interestingly, when the manipulation was prosodic in nature (i.e., either vowel lengthening or a pitch variation) but lexically relevant to differentiate the meaning of words (such as in Japanese) the lateralization was still left-hemispheric suggesting that not the manipulation per se but the linguistic impact might play a crucial role (Minagawa-Kawai, Mori, Furuya, Hayashi, & Sato, 2002; Minagawa-Kawai et al., 2007; Sato, Sogabe, & Mazuka, 2007; Sato et al., 2010). These findings highlight the importance of fNIRS in assessing hemispheric lateralization for example to differentiate whether the processing acts at a phonological or prosodic level. Even though many of these contrasts elicited differential ERP effects in the EEG, information about lateralization is not reliable in the EEG.

fNIRS results concerning the more complex interaction between lexicon, semantics, prosody, and syntax at the sentential level revealed a left-hemispheric activation already in newborns when forward speech was compared to backward speech (Peña et al., 2003) or sentences were compared to music (Kotilahti et al., 2010). Similarly, 4-month-old infants showed a left-hemispheric dominance for sentences presented in the native compared to a second language and showed a right hemispheric lateralization with regard to emotional vocalizations (Minagawa-Kawai et al., 2011). In adults, a left-hemispheric recruitment was confirmed when sentences were integrated in stories as well as when syntactically correct and incorrect sentences were confronted (Noguchi, Takeuchi, & Sakai, 2002; Sato, Takeuchi, & Sakai, 1999). With respect to prosodic manipulations, a right-hemispheric dominance was observed very early (from 3 months onwards) and confirmed also in 4-year-old children (Homae et al., 2006; Wartenburger et al., 2007).
Results on lateralization fit very well with the *Dynamic Dual Pathway Model* (Friederici & Alter, 2004) postulating a left-hemispheric recruitment for segmental aspects such as phonology, lexico-semantics, and syntax and a right-hemispheric recruitment for suprasegmental aspects such as prosody.
Interestingly, at the sentential level a lateralization was observed already during the first months of life, whereas at the single word level it seems to establish later on. This is plausible as identifying linguistic aspects when the acoustic speech stream is longer in duration (such as in sentences) is much easier than extracting regularities from single words presented in isolation. Thus, when the context is less demanding an efficient unilateral hemispheric recruitment seems to emerge earlier (Corballis, 2009; Ringo et al., 1994).

A hemispheric asymmetry was furthermore confirmed in newborns when they were presented with 9 s long acoustic stimuli containing either fast or slow acoustic transitions (Telkemeyer et al., 2009).
Finally, the article discusses that the detection of statistical regularities in an acoustic speech stream is a prerequisite for successful language acquisition and confirms that such a sensitivity visible in increased activations for immediate repetitions in contrast to random sequences is already present at birth (Gervain et al., 2008).
Furthermore, the article discusses that dynamics of lateralization are not purely linguistically driven but rely also on the acoustic speech input. Based on the *multi-time resolution hypothesis* (Poeppel et al., 2008) which assumes that fast transitions in the acoustic input should give rise to more bilateral activations and slow transitions to right-dominant activations, fNIRS findings confirm this pattern already in newborn infants suggesting very early sensitivity to the acoustic features of sounds (Telkemeyer et al., 2009).

6.2 How does the adult brain process native and non-native phonotactic rules under passive listening conditions?

Rossi, S., Jürgenson, I.B., Hanulikova, A., Telkemeyer, S., Wartenburger, I. & Obrig, H. (2011). Implicit processing of phonotactic cues: Evidence from electrophysiological and vascular responses. *Journal of Cognitive Neuroscience, 23(7),* 1752-1764.

When listening to a foreign language for the first time, we simply hear a connected acoustic stream. Because in between of the single words no pauses occur it is difficult to identify where a word begins and where it ends. Small infants but also adults confronted with a foreign language have to first master this task in order to subsequently be able to identify the correct word form and assign a meaning to the single word (Sebastián-Gallés, 2007). Prelexical cues such as stress pattern, allophonic details, and phonotactic constraints aid speech segmentation and thus improve word recognition (McQueen, 2007). Phonotactics describes the permissible phoneme combinations in a given language (Trask, 1996). Thus, /br/ can be a possible combination at the onset of a German or English word (e.g., /bread/) but /bz/ is not allowed at the onset of a word in these languages. This consonant cluster, however, might be permissible in other languages such as Slavic languages. Phonotactic constraints can act on word onsets, nuclei, and coda and help in identifying word boundaries (McQueen, 1998). Behavioral studies in adult listeners ascertained an interference of native phonotactic rules on the processing of a second language (Weber & Cutler, 2006).

The present study aimed at investigating neuronal correlates of phonotactic processing, (1) because neuroscientific evidence is scarce in this regard and (2) in order to measure implicit processing. Most previous studies (Friedrich & Friederici, 2005; McQueen, 1998; Weber & Cutler, 2006) included different tasks which had to be consciously performed. We were interested in the implicit processing during passively listening to phonotactically native and non-native pseudowords without having to perform any task. Two neuroscientific methods were applied simultaneously: the electroencephalography (EEG) and the functional near-infrared spectroscopy (fNIRS). The former method excellently tracks temporal changes in the range of milliseconds. The latter providing a better spatial resolution than EEG allows for the assessment of brain areas recruited during a specific processing. Furthermore, the method is silent and easy combinable with EEG.

With respect to the EEG, we analyzed event-related brain potentials (ERPs) focusing on the N400 component. This centro-parietally distributed ERP component around 400 ms was reliably found in relation to lexico-semantic processes in sentential contexts but also at the word level (Kutas & Federmeier, 2011). The N400 amplitude was found to show a U-shaped trajectory resulting in reduced amplitudes when lexical access is less demanding but also in smaller amplitudes when no lexical access can be reached. Pseudowords compared to real words, for example, show an increased amplitude as they need more processing resources compared to the familiar real words (Bentin et al., 1985; Chwilla et al., 1995; Soares et al., 1991). When comparing, however, pseudowords conforming to phonotactic rules of a native language compared to a foreign language the larger N400 amplitude was observed for native rules as non-native ones are interpreted as nonwords not necessitating any lexical access (Friedrich & Friederici, 2005).

Although some neuroimaging evidence on lexical and prelexical processing is available (Raettig & Kotz, 2008), no specific neuroimaging study focused directly on processing of native versus non-native phonotactic rules.

Monolingual adult subjects with German as native language participated in the study in which they passively listened to monosyllabic CCVC (consonant-consonant-vowel-consonant) pseudowords either corresponding to phonotactic rules of their native language (i.e., legal or native rules) or not (i.e., illegal or non-native rules). The phonotactic manipulation was created at pseudoword onsets by manipulating one consonant of the initial consonant cluster resulting in pairs of pseudowords (native /*br*op/ versus non-native /*bz*op/). In contrast to a previous EEG study (Friedrich & Friederici, 2005) also investigating native and non-native phonotactic rules in adults and children, non-native consonant clusters in the present study were controlled for legality in one other language, namely the Slovak language, in order to prevent from mixing of phonotactic rules of different languages. Slovak is an Indo-European language belonging to the West Slavic language group featuring many more consonant combinations at syllable onset than German or English (Hanulikova, 2009). Controlling the material in such a way also allowed to a priori exclude subjects having been exposed to Slavic languages. Native and non-native pseudowords were spoken by a German/Slovak early bilingual speaker with no foreign accent in either of the two languages. In order to assess a potential impact of prosodic aspects on the processing of phonotactic rules, all stimuli were spoken in adult-directed (ADS) and infant-directed speech (IDS). IDS is characterized by an increase in pitch, a longer duration, and a high phonological clarity (Soderstrom, 2007), thus aiding language acquisition especially in young infants. All stimuli were presented acoustically via loudspeakers in a pseudorandomized fashion while simultaneous EEG (with 59 electrodes equally distributed over the scalp) and fNIRS (with 8 light emitters and 4 light detectors resulting in 12 channels covering bilateral fronto-temporal areas) were assessed.

ERP results showed larger N400 amplitudes for native compared to non-native phonotactic rules. This is in line with previous studies (Friedrich & Friederici, 2005) extending the findings however to the fact that this differential processing occurred also without any task. Thus, the underlying mechanisms seem to work implicitly and do not necessitate specific attention to the phonotactic or lexical features. The larger N400 for native rules indicates that adults can use prelexical cues and initiate lexical search processes even without the occurrence of a lexical context.

fNIRS results nicely complement ERP findings in that they also reveal an increased activation for native compared to non-native rules. While ERPs did not show any hemispheric lateralization effect, fNIRS revealed a clear left-hemispheric dominance. This fits with assumptions postulated in the *Dynamic Dual Pathway Model* (Friederici & Alter, 2004). The model assumes a left-hemispheric processing for segmental information such as phonology, lexico-semantics, and syntax and a right-hemispheric dominance for suprasegmental aspects such as prosody. Because phonotactic rules are phonological cues impacting lexical processing it is plausible to assume a left-hemispheric recruitment. Furthermore, phonotactic aspects are fast segmental acoustic cues which are also assumed to be predominantly supported by the left hemisphere (Hickok & Poeppel, 2007; Poeppel et al., 2008; Telkemeyer et al., 2009). The activations found in the fNIRS were localized in fronto-temporal and temporal areas of the left hemisphere. Activations in these areas were often observed in relation to phonological and lexical processing (Bookheimer, 2002; Kotz, Cappa, von Cramon, & Friederici, 2002; Lau et al., 2008; Vigneau et al., 2006).

Some fMRI studies found left temporal activations in relation to phonemic perception (i.e., when native phonemes were contrasted with non-native ones) (Hara, Nakamura, Kuroki, Takayama, & Ogawa, 2007). Even though phonotactic and phonemic processing share several mechanisms, in our study a pure phonemic processing can be excluded as all phonemes used belonged to the subjects' native language repertoire. Solely the combination of these phonemes violated phonotactic rules of the native language.

fNIRS provides only a rough topographical resolution. Thus, it is not clear from our study whether more frontal or temporal areas are the driving force underlying phonotactic processing. An fMRI study (Vaden et al., 2011) found increased activations in the left inferior frontal gyrus (IFG) for phonotactically more frequent stimuli compared to less frequent ones. Subjects in this study had to perform a pseudoword detection task explicitly triggering semantic control and selection mechanisms. It was proposed that the IFG is involved in task-related lexical search and control (Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005). Because in our study no task was implemented and subjects had only to passively listen to the pseudowords, it seems more plausible to assume a stronger temporal engagement supporting phonotactic processing. The detailed investigation of topographical aspects of phonotactic processing was addressed in Experiment 2 of the present habilitation treatise.

With respect to the introduced different speech mode, adult- versus infant-directed speech, neither the EEG nor the fNIRS showed processing differences suggesting no prosodic impact in already fully language-competent adult listeners.

In sum, results from both neuroscientific methods nicely show corresponding results with respect to activation differences between the experimental manipulations of native and non-native phonotactic rules. However, these findings also emphasize the importance of multi-methodological approaches as only fNIRS revealed a clear left-hemispheric dominance confirming phonological and lexical processes underlying phonotactics.

6.3 How does a lesioned brain process language-specific and universal linguistic features?

Obrig, H., Mentzel, J. & Rossi, S. (2016). Universal and language-specific sublexical cues in speech perception: a novel electroencephalography-lesion approach. *Brain, 139,* 1800-1816.

Each language consists of regularities which are unique to this language and which have to be acquired individually during language acquisition. In contrast to these language-specific constraints, universal linguistic preferences also guide language acquisition and language processing in general. Such a differentiation was originally postulated by Noam Chomsky in his concept of *Universal Grammar* (UG) included in the *Principle and Parameter Theory* (Chomsky, 1981; Chomsky, 1976). According to this theory, the human language system consists of principles which are universal to all languages as well as parameters that vary across languages. UG is considered to be innate. In particular, Chomsky assumes that newborns are equipped with innate cognitive and computational abilities (so-called Language Acquisition Devices) before concrete language experience which allow such a fast language acquisition. Taking phonotactics as an example, the specific legal combinations of phonemes can be considered language-specific parameters. However, universal preferences for specific sonority profiles of phoneme sequencing have been suggested to represent universal phonological "well-formedness" (Berent, 2013; Berent, Everett, & Shimron, 2001; Clements, 1990). In order to identify brain areas supporting processing of universal and language-specific constraints, patients with a chronic left-hemispheric brain lesion compared to age-, sex-, and education-matched controls were investigated.

In each participant electrophysiological data (EEG) as well as behavioral data were assessed. The EEG experiment consisted in the acoustic presentation phonotactically legal - native (i.e., *br*op) and illegal - non-native (e.g., *bz*op) monosyllabic CCVC (consonant-consonant-vowel-consonant) pseudowords representing language-specific characteristics (i.e., forward speech). Legality was defined with respect to the participants' native language German. Illegal pseudowords complied with phonotactic rules of the Slovak language, a foreign language to all participants. This forward condition was compared to the digitally reversed presentation of half of the legal and illegal pseudowords (i.e., reversed speech). The differentiation between forward and reversed speech results in a universal contrast as even though the same acoustic features and frequencies are contained in the reversed speech condition, they partially violate prelexical structure of human speech and are rich in universally dispreferred phoneme combinations. Important is, however, that the reversed speech condition is sufficiently language-like to activate the language-related brain network (Binder et al., 2000; Stoppelman, Harpaz, & Ben-Shachar, 2013). Participants had to perform a repetition detection (i.e., press a button whenever the same pseudowords were presented in succession) during the EEG assessment in order to increase overall attention to the stimuli without directly pointing the attention to the linguistic features per se. In total, 27 EEG electrodes were assessed. Event-related brain potentials (ERPs) with a focus on lexical processing components around 400 ms (Kutas & Federmeier, 2011) were assessed. In patients, additional clinical tests taken from the LEMO test battery (Stadie, Cholewa, & De Bleser, 2013) were administered to assess phonological, lexical, and semantic competence.

Behavioral and ERP data were correlated with lesion-based data from a structural MRI scan in a novel approach. This approach represents an extension of the "voxel-based lesion-symptom mapping" (VBLSM) (Bates et al., 2003) in that ERPs instead of behavioral measures were correlated with the lesion topography. Thus, for each patient a high-resolution structural MRI scan was acquired in order to assess the extent of the lesion. Lesion delineation was performed manually in each patient in all planes (axial, coronal, and sagittal) for each slice of the T_1 image. An overlap of all lesions across patients was afterwards performed resulting in a binary voxel-wise lesion information (lesioned or not lesioned) which could then be correlated with ERP differences acquired during the EEG experiment. Only lesioned voxels which were affected in at least 10% of patients were included in the analysis.

ERP results revealed a stronger negativity for non-native versus native language-specific phonotactic rules as well as for reversed compared to forward speech. Interestingly, similar processing mechanisms were observed in patients and healthy controls. This result is striking considering that pseudowords were presented without any semantic context which represents a quite complex task for patients. The clinical data of the patients, however, confirm that phonological, lexical, and semantic competences of patients were quite unimpaired despite brain lesions covering areas in the language network. Also task performance during the behavioral repetition detection task during the EEG experiment was equally high in patients and controls suggesting a good attentional level in both groups. These favorable prerequisites might have contributed to the similar processing mechanisms in patients and controls suggesting a high brain plasticity during language recovery. ERP differences with respect to the language-specific contrast were found around 400 ms. This is in line with previous studies in young healthy subjects (Friedrich & Friederici, 2005; Rossi et al., 2011, 2013) and suggests successful lexical processing. In contrast to these studies, however, the direction of effects was reversed. In Rossi et al. (2011; 2013) which introduced a larger set of the same stimuli used in the present experiment, native phonotactic rules gave rise to a larger N400 component compared to non-native rules. In the present study, however, non-native rules elicited a larger negativity. Whereas in the previous studies (Rossi et al., 2011; 2013) this finding was interpreted as a successful lexical access for familiar phonotactic rules and a deselection of illegal (i.e., non-native) rules which are not relevant for the subjects' native language, the interpretation does not completely hold for the present experiment. Some other domain-general processes might have contributed to these findings. Larger N400s were often found in unexpected trials compared to expected ones (e.g., Kutas & Federmeier, 2011). Also in the present experiment non-native phonotactic rules were more unexpected/unfamiliar than native rules and thus gave rise to increased negativities. Similarly, larger negativities were found for reversed in contrast to forward speech. Moreover, reversed speech showed even more increased negativities than both forward conditions. Thus, the more unexpected an information seemed to be, the larger was the negativity. This effect might have been at least partially mediated by attentional effects. Interestingly, the N400 in younger adults (Rossi et al., 2011) who only passively listened to pseudowords without performing any specific task was larger for native phonotactic rules. In the present study participants had to carefully pay attention to each stimulus in order to perform the repetition task. Thus, attention was increased to native and non-native pseudowords as well as to pseudowords played in a reversed manner to an equal degree.

Furthermore, it was shown that with increasing age attentional functions also alter and differentially impact language processing (Shafto & Tyler, 2014). Maybe a change in attention allocation for new/unexpected information also occurred in our elderly subjects. Prefrontal activations in elderly are subject to changes especially when more attention or executive functions are required during experimental tasks (Davis, Zhuang, Wright, & Tyler, 2014; Shafto & Tyler, 2014). Thus, the reversed ERP effects observed in the present study seem to be affected by both age and changing attentional resources. Whether one component is driving this effect stronger than the other is still unclear. Disentangling whether aging or task demands or both contribute to this effect must be addressed in future studies.

Differential ERP effects with respect to the universal contrast (forward versus reversed speech) were observed not only in time windows around 400 ms but also in an earlier one, corresponding to the P2 component. Increased P2 amplitudes were present for forward compared to reversed speech. A similar increase was found for native compared to non-native pseudowords (Rossi et al., 2013) and might reflext the phonological mapping negativity (PMN). This component has been shown to be sensitive to prelexical information involving auditory phonological processing (i.e., mismatching expectation about phonological information) (Connolly & Phillips, 1994; Desroches, Newman, & Joanisse, 2008; Newman & Connolly, 2009). It has been furthermore suggested to be modulated by directing attention to relevant auditory cues such as in our study to forward speech (De Diego Balaguer, Toro, Rodriguez-Fornells, & Bachoud-Lévi, 2007; Reinke, He, Wang, & Alain, 2003).

ERP-lesion analyses revealed that language-specific ERP modulations correlated with the middle to anterior portion of the middle and superior temporal gyrus, whereas ERP differences concerning universal differentiation projected to inferior and posterior parietal areas including the angular and supramarginal gyrus. Thus, the former finding corresponds to the ventral path between anterior and posterior brain regions considered an interface between phonological and lexical processing but also allowing combinatorial and semantic processing (Friederici, 2015; Hickok & Poeppel, 2007). This is in line with our language-specific results as phonotactic rules are phonological cues which however have an impact on lexical processes especially during word learning. Interestingly, previous fMRI studies comparing high versus low phonotactic frequency in words identified brain regions in the left inferior frontal gyrus (IFG) (Vaden et al., 2011). This is not in contrast to our results if we consider the IFG to be involved in task-related lexical search and control mechanisms as was proposed by Badre, Poldrack, Paré-Blagoev, Insler, and Wagner (2005). Indeed, subjects in the Vaden et al. (2011) study had to perform a pseudoword detection task explicitly triggering semantic control and selection mechanisms. We also found support for such an interpretation in our clinical-lesion correlations. Left IFG activations correlated with performance during the semantic control task. The latter projection to parietal areas for universal constraints resembles the dorsal stream found to be involved in phonologically driven categorization and syntactic processes (Friederici, 2015; Hickok & Poeppel, 2007). Universal phonological preference, thus, seems to be driven by intact brain regions of this dorsal stream. These findings indicate a clear separation between a ventral and a dorsal stream, the former providing a language-specific link between phonological and lexical processing and the latter acting on universal phonological preference.

The present study provides an innovative approach to determine brain topography of linguistic features. The approach correlates ERP measures with lesion mapping in patients. Findings showed correlations resembling ventral and dorsal language pathways supporting language-specific and universal language processing. This further provides evidence for a dissociation between principles and parameters as postulated by Chomsky (1981) some decades ago. The importance of multi-methodological approaches becomes clear in the present study. EEG results in isolation did not indicate any statistical difference between patients and controls. Lesion-Behavior/ERP mapping however, revealed brain areas associated with impaired behavioral performance or electrophysiological modulations. Thus, this new approach can provide a better understanding of the topography of the complex language network.

6.4 Can adults learn new native and non-native words through mere passive exposure?

Rossi, S., Hartmüller, T., Vignotto, M. & Obrig, H. (2013). Electrophysiological evidence for modulation of lexical processing after repetitive exposure to foreign phonotactic rules. *Brain & Language, 127*, 404-414.

Passive Listening Experiment

Not only infants have to master the challenging task of acquiring language. Also during adulthood we are constantly confronted with new languages which we have to acquire for private or professional reasons. The globalization including the internet confronts us with a variety of languages and information in different languages. Furthermore, bilingualism represents a pivotal issue with respect to immigration, more than ever an issue. The establishment of global communicative languages without eclipsing single languages is a challenging endeavor. Multilingualism represents an extremely precious cultural good, thus needing to be preserved. All the more important we have to understand the underlying language learning mechanisms in adulthood in order to establish the optimal learning setting in which a high proficiency can be acquired in a second language. Even though an early age of acquisition is beneficial for achieving a high proficiency, also a late onset can lead proficiency towards a native-like attainment by means of sophisticated brain plasticity (Rossi et al., 2006). The present article includes two EEG experiments. The first experiment (Passive Listening Experiment) investigated the electrophysiological temporal dynamics of native and non-native phonotactic rule processing in healthy monolingual adults when learned through passive acoustic repetitive exposure over three consecutive days.

As already mentioned previously, phonotactic rules are prelexical cues describing the permissible combinations of phonemes in a given language (Trask, 1996). These linguistic rules were selected because they aid segmentation of an acoustic speech stream into single units and as a consequence improve word recognition and word learning (Jusczyk, 1999; McQueen, 1998). Monolingual adults having been exposed to phonotactic regularities of their native language (in our case German) can successfully differentiate between pseudowords adhering to phonotactic rules of the native language and non-native rules (Friedrich & Friederici, 2005; Rossi et al., 2011). But what happens if both native and non-native rules undergo massive repetitive exposure through passive listening? Especially non-native rule processing was in the focus of investigation in order to see whether fully language-competent monolingual adults are still capable of acquiring new foreign linguistic rules in a very short learning period over three days. In order to assess fast temporal variations in neuronal processing of word learning we focused on the N400 component reflecting lexico-semantic processes (Kutas & Federmeier, 2011). The N400 amplitude was found to be sensitive to phonotactic regularities and showed larger N400 amplitudes for pseudowords conforming to phonotactic rules of a native language compared to a foreign language suggesting that non-native rules are interpreted as nonwords not triggering any lexical access (Friedrich & Friederici, 2005; Rossi et al., 2011).

In language learning contexts the N400 was found to increase in amplitude to pseudowords compared to real words after 14 hours of classroom instruction (McLaughlin et al., 2004) and to reduce when pseudowords conforming to native phonotactic rules are learned in combination with pictures of familiar real objects (Dobel, Junghöfer, et al., 2009). When however pseudowords learned associatively with pictures contained non-native phonemes, an increase in N400 was attested suggesting that they lost their nonword status and started to be integrated in the phonetic repertoire (Dobel, Lagemann, et al., 2009). In order to investigate the impact of a mere passive listening exposure without any semantic context we investigated German monolingual adult participants in a pretest, training, and posttest design. In order to assess learning effects establishing over a longer time period participants were assessed on three consecutive days. By introducing also a pretest on each day potential effects arising from the overnight consolidation (Davis, Di Betta, Macdonald, & Gaskell, 2008) could be assessed as well. During pre- and posttests monosyllabic CCVC (consonant-consonant-vowel-consonant) pseudowords conforming to native (i.e., German) phonotactic rules (e.g., *br*op) were compared to pseudowords of non-native rules (e.g., *bz*op). Non-native rules were controlled for in such a way that they were legal in one other language, the Slovak language. Slovak was selected as it allows for much more phoneme combinations as German (Hanulikova, 2009). Such a procedure allowed a priori excluding subjects having been exposed to Slavic languages. In order to maintain subjects' attention to the stimuli during pre- and posttests, subjects performed a word monitoring task. This task consisted in the presentation of the written form of one pseudoword after 4 heard pseudowords requiring a button press decision whether the written word corresponded to one of the last heard pseudowords or not. During training, half of native and non-native pseudowords were repetitively presented acoustically without any specific task. Each pseudoword was repeated four times in a pseudorandomized fashion. This allowed investigating the impact of a massive exposure on trained items compared to untrained items only presented once during pre- and posttests, respectively. EEG was continuously recorded from 59 electrodes during pretest, training, and posttests. After the electrophysiological assessment, subjects had to perform a behavioral recognition test on each day in which they were presented with the trained and completely new pseudowords and they had to decide whether or not they had heard them during the experiment.

Results of the behavioral recognition test showed an increase in performance over the three learning days suggesting successful learning.

ERP data were first analyzed only on pretest of day 1 in order to replicate findings on phonotactic differentiation of the previous study without a learning context (Rossi et al., 2011). Here no differences between trained and untrained items were expected, thus they were collapsed to compare native and non-native rules. As expected, a larger N400 for native phonotactic rules was present replicating our previous findings. Results of the passive listening learning setting revealed a decrease in N400 with increasing passive listening exposure for both native and non-native trained items as well as for native untrained items. The modulation with respect to native rules reflect habituation effects in the direction of a more "word-like" status of these pseudowords with increasing exposure (Dobel, Junghöfer, et al., 2009).

The decrease in N400 for non-native rules indexes successful deselection of non-native items which are not linguistically relevant for the subjects' native language, at least in an initial learning stage and when only acoustically presented without any semantic context. The non-native untrained items, however, did not show any difference over time suggesting that passive exposure to unfamiliar rules was not sufficient to elicit a learning effect.

ERP data were also analyzed immediately during training comparing the modulation of native and non-native pseudowords. Non-native pseudowords confirmed the decrease in N400 amplitude from day 1 to day 2 and 3 and indicate that already during the learning process this deselection process started. Native pseudowords, on the other hand, did not give rise to any modulation over the three days suggesting that the training impacted the N400 only later on during posttests when trained and untrained items had to be processed but not immediately during the learning process.

6.5 Can adults learn new native and non-native words through semantic categorization?

Rossi, S., Hartmüller, T., Vignotto, M. & Obrig, H. (2013). Electrophysiological evidence for modulation of lexical processing after repetitive exposure to foreign phonotactic rules. *Brain & Language, 127*, 404-414.

Semantic Categorization Experiment

The Semantic Categorization Experiment of the present article (Rossi, Hartmüller, Vignotto, & Obrig, 2013) was similarly designed as the Passive Listening Experiment. Healthy adult monolingual subjects underwent a pretest, training, and posttest on three consecutive days. Pre- and posttests were identical to the Passive Listening Experiment. The training, however, was designed to assess N400 changes when repetitive exposure consisted in a categorization task, thus introducing a protosemantic learning context. The aim was to test which impact a semantic learning context has on the processing of native and non-native phonotactic rules and to compare the results to the Passive Listening Experiment. During training of the Categorization Experiment half of native and non-native pseudowords presented during pre- and posttests were trained. After the presentation of each pseudoword, subjects had to learn whether the pseudoword belonged to the arbitrary category A or B. They should press a button, respectively. After each response a visual feedback (happy or sad smiley) was provided informing subjects whether their response was correct or not. Thus, at the beginning of training, responses were quite intuitive and progressively subjects learned which pseudoword belonged to which category. Half of native and non-native pseudowords were assigned to category A and B, respectively. It is important to note that this categorization task introduces an arbitrary mapping between a word's lexical form and its meaning and thus creates a protosemantic context without, however, relating the categorization with phonotactic properties of the pseudowords. Similar to the Passive Listening Experiment each pseudoword was presented four times in a pseudorandomized fashion.

EEG recordings and analyses were analogous to the Passive Listening Experiment. Again, subsequent to the electrophysiological measurement, a behavioral recognition test was administered in which subjects had to indicate whether the pseudowords were present during training or not. Additionally, the behavioral responses during training, thus the performance of categorization across the three learning days could be analyzed here.

Behavioral results of the recognition test and the judgement during the categorization task showed a performance increase over the three learning days.

ERP results concerning native trained and untrained items showed a similar decrease in N400 as for the Passive Listening Experiment suggesting that habituation processes for language rules belonging to the subjects' native language repertoire are independent of the type of exposure they are confronted with.

With respect to new trained non-native rules, however, results show an abolishment of the decrease in N400 observed for passive listening and for untrained non-native rules even an increase in N400. Because linguistic salience increases through the protosemantic context of the Categorization task, trained items increase in N400 but this is partially neutralized by the ongoing repetitive exposure leading to a decrease in amplitude. Thus, for trained non-native items no difference occurred over time. For untrained non-native items, on the other hand, the enhanced N400 is driven by the increase in linguistic salience without habituation and thus without a decrease in N400 through repetitive exposure and hence the N400, overall, increases over time. These findings fit with results of Dobel, Lagemann, et al. (2009) which also found an increase in N400 for pseudoword consisting of foreign phonemes learned in association with pictures of real objects. Taken together, the categorization task led to an attempt to integrate these foreign rules into the phonotactic repertoire. Intriguingly, this happens in a very short period over three consecutive days and in a protosemantic context pointing to arbitrary rule learning and not directly providing an associative learning context such as for example between a new word and a semantically related object.

In sum, results of both experiments suggest that repetitive exposure, irrespective of its nature, decreases N400 amplitudes of familiar native language rules. Non-native rules, however, are strongly impacted by the kind of exposure they experience. Whereas a pure passive listening only reduces the N400 and thus acts as a habituation similar to familiar linguistic rules, a protosemantic context is able to abolish this decrease and even increase the N400 suggesting the beginning of integration of foreign linguistic rules in the lexicon. This plastic adaptation of the brain is astonishingly fast as it occurs over few training session at the very beginning of exposure to foreign linguistic rules. And all this happened in an arbitrary categorization task without concrete semantic context directly relating the new word form to a specific object.

6.6 How does a semantic-associative training impact neuronal processing of native and non-native rules in 6-month-old infants?

Obrig, H., Mock, J., Stephan, F. Richter, M., Vignotto, M. & Rossi, S. (2017). Impact of associative word learning on phonotactic processing in 6-month-old infants: A combined EEG and fNIRS study. *Developmental Cognitive Neuroscience, 25*, 185-197.

At birth newborns are prepared to learn every language they will be confronted with. Indeed, also during the last trimester of pregnancy the auditory system is functional and slow linguistic aspects such as prosodic features can be already heard by the fetus (Abrams & Gerhardt, 2000; Hall, 2000). Faster acoustic features which correspond to the fine-grained differentiation between single phonemes emerge only in the extra-uterine environment after birth.

From birth on, newborns possess the universal ability to distinguish virtually all linguistic contrasts including those irrelevant for their native language (Calvo, García, Manoiloff, & Ibáñez, 2015; Gervain, Berent, & Werker, 2012). However, as infants grow older, this ability is subject to a *perceptual narrowing* or "language tuning", thus becoming more committed to speech sounds compared to other biological sounds (Shultz, Vouloumanos, Bennett, & Pelphrey, 2014; Vouloumanos, Hauser, Werker, & Martin, 2010) and more importantly it gets more devoted to the native language while impoverishing sensitivity towards non-native features (Kuhl et al., 2006; Minagawa-Kawai et al., 2007; Werker & Tees, 1984). Perceptual narrowing is a very important process predicting later language abilities and thus being correlated with later language impairments (Kuhl et al., 2008). Cortical specialization and neuronal plasticity accompanies these changes in sensitivity towards the native language. Seminal findings showed that newborns already at birth are able to distinguish their native language from other rhythmically different languages (Kuhl, 2004; Mehler et al., 1988; Nazzi, Bertoncini, & Mehler, 1998). Several behavioral studies showed an increased sensitivity towards phonemes of the native language during the second half of the first year of life (Eimas et al., 1971; Kuhl et al., 2006; Kuhl, 2014; Ortiz-Mantilla, Hämäläinen, Musacchia, & Benasich, 2013; Rivera-Gaxiola, Klarman, Garcia-Sierra, & Kuhl, 2005; Werker & Tees, 1984). By using neuroscientific methods differential processing between native and non-native linguistic regularities was even found at a younger age (Friederici et al., 2007; Rossi et al., in prep.).

At the beginning of language acquisition, infants are confronted with a continuous acoustic speech stream which they have to successfully segment into smaller units in order to identify single words and be able to assign them a specific meaning. In order to segment the speech stream infants use several prelexical cues such as stress pattern and phonotactics (Cutler, 1996; Jusczyk, 1999; Sebastián-Gallés, 2007). Phonotatics describes the eligible combinations of different phonemes, in a given language (Trask, 1996). Several behavioural studies (Friederici & Wessels, 1993; Jusczyk et al., 1993; Mattys et al., 1999; Mattys & Jusczyk, 2001) found that 9-month-old infants prefer listening to sound sequences which are legal with respect to their native language whereas 6-month-olds listen equally long to phonotactically legal and illegal sounds. Neuroscientific studies revealed differential processing already at 6 months of age (Rossi et al., in prep.).

In order to learn the meaning of words, infants use several learning strategies. One important strategy is semantic-associative learning. Here an object is associated with a specific meaning. This process starts very early, prior to language production, and was termed *fast mapping* (Carey & Bartlett, 1978). Several mechanisms impact word learning such as *statistical learning* (i.e., what is more frequently combined should be learnt), the *whole object constraint* (i.e., a word primarily labels a whole object rather than single parts), the *noun-category bias* (i.e., a word is assumed to extend to other members of the same category), and the *mutual exclusivity constraint* (i.e., if an object has already a name the new word will refer to another object) (Aslin, 2017; Carey, 1978; Markman, 1990; Markman & Hutchinson, 1984; Saffran et al., 1996). Phonotactics does not only help to segment the speech input but once segmented it aids to create a link between the new word and a semantic meaning (Gervain & Mehler, 2010). This bottom-up process is complemented by top-down processes. These assume that acquired lexico-semantic knowledge fosters statistical phonological learning and thus segmentation (Bortfeld et al., 2005). This assumption is based on the observation that already prelingual infants at 3 and 6 months of age show abilities of fast mapping, thus even prior to actual word production (Bergelson & Swingley, 2012, 2015; Friedrich & Friederici, 2017). These processes are at least partially driven by domain-general aspects such as attention, memory, and general cognitive/learning abilities.

In the present study we aimed at investigating this top-down influence by studying 6-month-old infants in an associative language learning context. We were especially interested in the impact of this associative learning context to the processing of native and non-native phonotactic regularities. Infants underwent a pretest, training, and posttest. During pre- and posttest, phonotactically native (with respect to the subjects' native language German) and non-native pseudowords were passively presented via loudspeakers. During training, half of native and non-native pseudowords were combined with pseudobjects. Six times the same pseudoword was correctly paired in a pseudo-randomized fashion with the same pseudoobject and six times incorrectly paired with six different objects as distractors. Such a design conforms to the rules of statistical learning, in that, what is more frequently combined should be learned (Aslin, 2017; Saffran et al., 1996). In order to direct infants' attention to the visual stimuli on the screen, a ring tone prior to the presentation of the pseudoobject was delivered from the loudspeakers near the monitor. During posttests, native and non-native pseudowords were divided into trained and untrained items in order to assess the direct impact of the training as well as potentially arising generalization effects to untrained items. In order to investigate immediate training effects (acting on short-term memory) as well as longer-lasting learning effects infants were assessed on three consecutive days. By introducing a pretest on each day, we additionally had the possibility to assess overnight consolidation effects (Friedrich & Friederici, 2011; Friedrich, Wilhelm, Born, & Friederici, 2015). Phonotactically native and non-native pseudowords were taken from a larger set of stimuli already successfully used in adults (Rossi et al., 2011). The pseudowords used in the present study, however, were presented only in infant-directed speech, a speech mode familiar to infants of most cultures worldwide. This speech mode is mainly characterized by an exaggerated intonation, a longer duration, and a clearer pronunciation (Soderstrom, 2007) and is thus assumed to aid word learning. EEG and fNIRS was simultaneously assessed by 24 electrodes equally distributed over the scalp and 16 fNIRS channels (resulting from 6 light emitters and 8 light detectors) positioned over fronto-temporo-parietal areas of both hemispheres.

Event-related brain potential (ERP) and fNIRS results showed reliable short-term (from pre- to posttests) learning effects. These appeared in an increase in negativity in the EEG and an increased activation in the fNIRS. Due to the broad effect for trained and untrained items as well as for native and non-native phonotactic regularities, one might assume that this effect could be mediated by an increase in attention to acoustic features of the speech stimuli, especially due to the presentation of the stimuli in infant-directed speech. Because, however, this short-term effect was predominantly present on the left-hemisphere (as evidenced by the fNIRS results), a more linguistically-oriented process has to be taken into consideration (Minagawa-Kawai et al., 2007; Rossi et al., 2012). Previous ERP studies (Friedrich & Friederici, 2011, 2017; Junge, Kooijman, Hagoort, & Cutler, 2012; Kooijman et al., 2005) found similar increases in negativity while passively familiarizing infants with new linguistic input, even without a semantic context. Thus, also the modulations found in our study seem to resemble familiarization processes relevant for memory encoding (Bauer et al., 2006; Borgström, Torkildsen, & Lindgren, 2015; Friedrich & Friederici, 2017) of new word forms. Interestingly, no stable long-term effects established over the course of the three learning days suggesting than long-term retention is not as mature at this young age (Friedrich & Friederici, 2011, 2017). The fact that this short-term increase in activation was present also in untrained items which were only acoustically presented during pre- and posttests but not trained within the semantic training indicates generalization mechanisms active already at 6 months of age. Results directly comparing trained and untrained items led to an increase in negativity in the EEG as well as to an enhanced activation in the fNIRS for trained items further supporting familiarization effects due to repetitive exposure resting upon these processes.

The impact of the semantic training was quite similar for native and non-native rules. These findings suggest that infants at this young age are not subject to strong influences arising from previous linguistic knowledge and are still open to learn new linguistic rules within an associative learning context. This fits with previous studies showing that older infants (around 18 months of age) learned pseudoobject-pseudoword associations but only if pseudowords conformed to phonotactic rules of the native language (Graf Estes et al., 2011; Graf Estes & Bowen, 2013). Even though the impact of the training on phonotactic rules was small, a significant differentiation between native and non-native phonotactic rules was though present. In the fNIRS this effect resulted in an increased activation for native rules either during posttests or at day 3. ERPs showed a reversed pattern, namely an increase in negativity for non-native rules at centro-parietal areas. This result is in contrast to previous studies in adults as well as older 19-month-old children (Friedrich & Friederici, 2005; Rossi et al., 2011) who found increased negativities for native rules. Two explanations may account for this phenomenon. (1) The presentation of stimuli in infant-directed speech might have increased attention to the most unfamiliar stimuli, thus to pseudowords of non-native rules. Similar orienting responses indexed by increased negativities in the EEG were found for novel, infrequent, or more salient stimuli, such as high- in contrast to low-frequency sounds, longer compared to shorter tones, or infrequent as compared to frequent visual stimuli (Clarkson, Clifton, Swain, & Perris, 1989; Courchesne, Ganz, & Norcia, 1981; Morrongiello & Clifton, 1984). Such orienting responses are guided by selective attention allocation and are mandatory for successful memory formation (Reynolds & Romano, 2016; Zarcone, van Schijndel, Vogels, & Demberg, 2016). Such an account also fits with our results.

(2) During infancy, inverted polarities were often observed as immature precursor components (Kooijman et al., 2013; Männel & Friederici, 2013). Because infants exposed to similar native and non-native phonotactic rules in the study of Friedrich and Friederici (2005) were older it might equally be plausible that the here observed reversed polarity might depend on immature neuronal processing mechanisms. Future studies will have to disentangle these two mechanisms by selectively manipulating attentional conditions. For example, it would be interesting to perform the present study in 6-month-old infants but using pseudowords spoken in adult- instead of infant-directed speech and compare the impact of a semantic associative training on native and non-native rule processing.

With respect to hemispheric lateralization a predominantly bilateral distribution was observable for the training effect. This result suggests an immature lateralization at this young age (Minagawa-Kawai et al., 2007; Rossi et al., 2012). The bilateral recruitment at younger ages or when task demands are high can be considered a compensatory mechanism. Such duplication represents, however, less efficient processing as it might necessitate too many neuronal resources and lead to interhemispheric conflict potentials slowing processing (Corballis, 2009; Ringo et al., 1994). An ongoing study of our research group in 18-month-old infants undergoing the same semantic associative training will provide important findings in this regard by attesting whether infants in the second year of life, when speech production also establishes, show an adult-like left-hemispheric lateralization. For the short-term increase in activation from pre- to posttest of the here presented study a stronger left-hemispheric dominance was observable suggesting more mature linguistic rather than domain-general familiarization effects at the basis of these modulations.

6.7 How do pragmatic cues impact word learning in monolingual and bilingual 5-year-old children?

Groba, A., De Houwer, A., Mehnert, J., Rossi, S.* & Obrig, H.* (2017). Bilingual and monolingual children process pragmatic cues differently when learning novel adjectives. *Bilingualism: Language and Cognition*

**shared last authorship*

Bilingualism was shown to improve cognitive skills. Bilingual adults, for example, have been found to outperform monolinguals in task which require switching between rules and thus show increased cognitive flexibility (Liu et al., 2015, 2014; Stocco & Prat, 2014). Furthermore, bilingual children show increased pragmatic skills such as a better understanding of deixis through pointing or eye gaze leading to enhanced reasoning about mental states of others and having a beneficial impact on theory of mind (Colunga et al., 2012; Farhadian et al., 2010; Greenberg et al., 2013; Yow, 2015; Yow & Markman, 2011). This advantage was assumed to originate from greater communicative challenges posited on bilinguals (Yow & Markman, 2011). Especially, during challenging word learning a more advanced use of pragmatic cues in bilingual children was observed (Yow, 2015). Learning novel adjectives represents such a challenging task during language development. All children have difficulties with remembering the entity's features and long-term retention of property labels such as color, shape, and texture words (Holland et al., 2015; Perry et al., 2016). One of the reasons for these difficulties may lie in the word learning principle *whole object constraint* describing that novel words predominantly refer to the whole object rather than to their properties (Markman, 1994). Another word learning mechanism, however, also impacts adjective processing, namely the *mutual exclusivity constraint* referring to the fact that if one object has already a name, a new name for the whole object will be rejected and an adjective interpretation preferred (Markman, 1990). Nevertheless, pragmatic cues such as gestures help children to identify the property of an object and thus aid novel adjective learning. Aim of the present study was to investigate a challenging word learning setting in bilingual and monolingual children. This is the first study addressing novel adjective learning through gestures as pragmatic cue in bilingual children. Apart from a few behavioral studies on adjective learning without pragmatic cues (Yoshida, Tran, Benitez, & Kuwabara, 2011), neuroscientific evidence in regard is even fewer. Thus, we investigated neuronal processing mechanisms while adjective learning in bilingual and monolingual children by means of functional near-infrared spectroscopy (fNIRS).

5-year-old German-Spanish bilingual and German monolingual children were assessed. Bilinguals were a quite homogeneous group who were exposed to both languages from birth, most of them speaking both languages at home with their parents. Children underwent a word learning task. Bilinguals took part in two sessions, one in German and one in Spanish within a two-week period. Monolinguals only took part once in the German session. The learning task was programmed as a computer video game in which they should help an astronaut buying presents for an alien's party. The presents were visually presented pseudoobjects labeled by a new word (either a nominalized adjective or a noun). Children had to select one of two pseudoobjects as present for the alien.

The experiment started with a familiarization phase in which two exemplars of the same novel pseudo-object rotated on their axes in a video-like fashion. In between, the object presentation stopped and a gesture (either a slow wave-like stroking or a pointing to the whole object gesture) was introduced either highlighting the property or category of the new object. The familiarization period was accompanied by a verbal input mentioning the new label of the object four times. The new words were integrated in a sentential context and time-locked to the gesture presentation. After the familiarization phase a forced-choice task followed in which two objects were presented and children had to select on a touch-screen monitor the object which corresponded to the new presented word. One object matched the previously presented object in surface property but not in shape (property match) and the other matched the previous object in shape but not in surface property (category match). The forced-choice task allowed a behavioral assessment of the interpretation of children for the previously learned association. After having selected the "presents for the alien" a happy alien was presented on the screen, irrespective of whether children selected a property- or category-match object. Neuronal activity was assessed during the familiarization phase by means of fNIRS. 9 light emitters and 14 light detectors measures 26 channels distributed over prefrontal, frontal, frontotemporal, temporal, and temporo-parietal brain areas in both hemispheres.

Behavioral results showed no differential processing between bilingual and monolingual 5-year-olds. This result was surprising as other studies attested increased abilities in pragmatic cue interpretation in bilinguals (Colunga et al., 2012; Yow, 2015; Yow & Markman, 2011). These studies, however, used pragmatic cues highlighting a noun or pronoun interpretation and not the adjectival interpretation. Hall, Williams, and Bélanger (2010) indeed found that descriptive gestures help 4-year-old children in learning adjectives but only when combined with a syntactic adjective context. Our learning context was much more difficult as no reliance on morphosyntactic aspects was present. Thus, findings suggest that a descriptive gesture in isolation seems not to be enough for correctly identifying a property of an object. Furthermore, our descriptive gesture was the same for all properties, thus decreasing transparency of the gestural property reference. This additionally introduced a difficulty which might have neutralized a difference between bilingual and monolingual children while consciously selecting either a category or property interpretation.

fNIRS results, however, demonstrated a clear difference between bilinguals and monolinguals. An increased activation in the right temporal cortex including the posterior part of the superior temporal sulcus (STS) was observed for bilinguals compared to monolinguals. This area was found in relation to processing nonverbal social cues for mental state attribution (Doré, Zerubavel, & Ochsner, 2015; Yang, Rosenblau, Keifer, & Pelphrey, 2015) and in theory-of-mind-related tasks of false belief (Kobayashi, Glover, & Temple, 2007). In particular, in monolingual adults the right posterior STS was related to understanding gestural and sociolinguistic processing (Deen, Koldewyn, Kanwisher, & Saxe, 2015). Neuroimaging evidence in children in this regard is scarce. However, an fMRI study in 13-year-old children suffering from autism spectrum disorder (ASD) and thus exhibiting reduced pragmatic skills showed a reduced right STS activation in response to co-speech gestures (Hubbard et al., 2012). This finding is supported by anatomical differences in ASD compared to controls reporting an atypical functional connectivity (Alaerts et al., 2015) as well as anatomical abnormalities of the STS in ASD (Boddaert et al., 2004). The increased activation in this brain region in bilingual compared to monolingual children supports the notion of enhanced pragmatic skills. Interestingly, we found the involvement of this area already in preschool children. Thus, this area seems to be mature already much earlier as previous studies showed.

Interpreting communicative intents was found to be associated with the activation of a large neuronal network including not only the STS but also the superior parietal cortex, the temporal parietal junction, and the prefrontal cortex (Enrici et al., 2010). In particular, no differential activation across groups was observed in the prefrontal cortex, often found to be associated with enhanced inhibitory control in general (Bialystok et al., 2010; Carlson & Meltzoff, 2008; Crivello et al., 2016; Mehnert et al., 2013) as well as a more efficient suppression of the whole object bias in bilinguals (Markman, 1994). Even though these prefrontal findings from the present study diverge from previous studies, they are in line with recent assumptions about neuronal plasticity effects caused by bilingualism. Apart from anatomical differences in gray and white matter in bilinguals, also functional differences were observed. It was proposed that a shift from frontal (in particular the anterior cingulate cortex - ACC and the dorsolateral prefrontal cortex - dlPFC) to posterior regions including the basal ganglia lies at the basis of increased neuronal efficiency observed in bilinguals (Abutalebi et al., 2012; Waldie, Badzakova-Trajkov, Miliivojevic, & Kirk, 2009). This shift was termed *bilingual anterior-to-posterior and subcortical shift* (BAPSS) (Grundy, Anderson, & Bialystok, 2017) and is assumed to reflect more efficient neuronal mechanisms when dealing with increased conflict situations arising when a rapid task switching or language switching is necessary (Stocco & Prat, 2014). Interestingly, a reversed pattern is observed in cognitive aging. The PASA (*posterior-anterior shift in aging*) model (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008) postulates age-related increases in frontal activity at the expense of a reduction of activity in posterior brain areas. This plastic change in older monolinguals could not be attested in bilingual elderly suggesting that due to the enhancement of posterior regions during young adulthood, frontal regions remain available for difficult cognitive task during older adulthood and thus do not need to shift as a compensatory mechanism (Gold, Kim, Johnson, Kryscio, & Smith, 2013; Grant, Dennis, & Li, 2014). In bilingual children no BAPSS was observed. Instead, an over-recruitment of frontal areas, especially of the ACC was observed (Jasinska & Petitto, 2013; Kobayashi, Glover, & Temple, 2008; Mohades et al., 2014). Grundy et al. (2017) suggest that this phenomenon might be a by-product of bilingual children' attempt to keep two languages in mind at an initial stage. Once development advances the brain recognizes the commonalities between the two languages and does not necessitate this over-recruitment of frontal regions anymore. A similar mechanism might have played a role in our bilingual children. Due to their constant balanced exposure to both languages from birth on and a high proficiency in both languages, their brain seems to have already established sufficiently efficient processing mechanism resembling those of young adult bilinguals. Thus, BAPSS seems to have at least started in our bilingual 5-year-old children resulting in no difference between bilinguals and monolinguals in frontal regions but in an increased activation for bilinguals in posterior temporal regions.

Finally, the present study furthermore highlights the importance of multi-methodological approaches. If we had performed only a behavioral study the conclusions would lead to a null effect. By the concomitant assessment of neuronal parameters it was possible to identify differences between bilingual and monolingual children. These differences might be at least partly influenced by conscious processes as behavioral selection of property or category match measures conscious selection processes. fNIRS assessment, on the other side, was performed directly during the learning phase thus assessing automatic and possibly unconscious processes.

7. General Discussion

7.1 Distinguishing language-specific and universal linguistic constraints

In order to be able to successfully understand language, not only the auditory organ must be functioning. Our brain is faced with the challenging task to decode the auditory signal, to segment it, to categorize it, to memorize it, and to interpret it. In order to fulfil this complex task it has to rely on several computational principles. Some of these are language-specific, meaning that they have to be acquired during language development because unique to the native language a person is confronted with. Other constraints are universal and probably domain-general. These represent basic mechanisms independent from each language but essential for language learning. This distinction between universal and language-specific constraints was already put forward by the American linguist Noam Chomsky in his concepts of *Universal Grammar* and *Principle and Parameter Theory* (Chomsky, 1976; Chomsky, 1981). Universal mechanisms are assumed to be present from birth on and represent cognitive and computational predispositions which guide infants through the fascinating journey of language acquisition. Universal constraints include for example the *structure-dependency principle* which defines the intrinsic knowledge that all sentences consist of phrases (Cook & Newson, 2014). Furthermore, the *Merge principle* describes that language is formed by combinatorial rules (Berwick & Chomsky, 2015; Chomsky, 1995; Everaert et al., 2015; Yang et al., 2017). This principle applies not only to syntax at the sentential level but also to the combinatory rules relevant for phonology and word learning (Yang et al., 2017). Universal constraints also contain universal preferences such as the sonority profiles of phoneme sequencing. They were assumed to reflect universal phonological "well-formedness" (Berent, 2013; Berent et al., 2001; Clements, 1990). Guided from these assumptions we wanted to compare universal to language-specific constraints during speech comprehension. We created a material of pseudowords either contrasting native and non-native phonotactic rules (language-specific contrast) or pseudowords played in a forward or reversed manner (universal contrast). Phonotactic rules represent the allowed phoneme sequences in a specific language (Trask, 1996). These rules are relevant during language acquisition as they aid segmentation of a continuous acoustic speech signal and once segmented support lexical search and integration (Friederici & Wessels, 1993; Jusczyk et al., 1993; Mattys et al., 1999; Mattys & Jusczyk, 2001). Universal constraints were operationalized as forward compared to reversed speech. Reversed speech is considered to violate phonological sequencing principles and thus being universally "dis-preferred". In Experiment 1 we acoustically presented phonotactically native and non-native pseudowords to healthy adult subjects while assessing brain activity by means of the combination of the electroencephalography (EEG) and the functional near-infrared spectroscopy (fNIRS). In Experiment 2, phonotactically native and non-native pseudowords presented either in a forward or reversed manner were assessed by means of EEG in healthy controls as well as patients having suffered from a brain lesion to the left hemisphere.

Event-related brain potentials (ERPs) were analyzed in the EEG and a modulation of the N400 component found. The N400 is a centro-parietally distributed negativity occurring around 400 ms post-stimulus onset and reflecting lexico-semantic processes (Kutas & Federmeier, 2011). Healthy adults in Experiment 1 revealed increased N400 amplitudes for phonotactically native rules compared to non-native ones. This result is in line with the only previous ERP study addressing phonotactic processing in adults (Friedrich & Friederici, 2005) suggesting that familiar phonotactic rules trigger lexical search processes while non-native rules are discarded because not relevant for the native language.

Our Experiment 1, however, did not include additional real words as well as pictures of objects presented concurrently as in Friedrich and Friederici (2005). Thus, no semantic context was created in our Experiment 1. This was intended as we wanted to investigate whether N400 modulations could also be elicited when native and non-native phonotactic rules have to be processed implicitly. This resulted to be the case as a reliable difference was found. In Experiment 2, we also found an N400 modulation, however, in a reversed pattern. Phonotactically non-native pseudowords gave rise to larger negative amplitudes than native rules. Importantly, both healthy controls and patients led to the same modulations which can be explained by the reduced symptoms ascertained also by means of neuropsychological tests. It should be noted that subjects in this experiment were older (mean age: 52 years) than in Experiment 1 (mean age: 24 years). Furthermore, whereas in Experiment 1 only the language-specific phonotactic contrast was presented, Experiment 2 included also the universal contrast. Considering the ERP results for this universal contrast, we found increased negative amplitudes around 400 ms for reversed (i.e., universally dispreferred) speech compared to forward speech. Thus, information which was more dis-preferred, unexpected, or unfamiliar elicited the largest negativity. These differential electrophysiological modulations can be explained by attentional factors. When different types of stimuli varying in familiarity were presented, enhanced attention may be directed to the most unexpected stimulus, thus leading to the largest N400 (for a recent review on auditory attention please refer to Schröger, Marzecová, & SanMiguel, 2015). Such an interpretation fits with orienting responses mostly found in infants suggesting the necessity to guide the learner to new important information for the sake of memorization (Clarkson et al., 1989; Courchesne et al., 1981; Morrongiello & Clifton, 1984; Reynolds & Romano, 2016; Zarcone et al., 2016). Indeed, in Experiment 5 in 6-month-old infants we also found a similar ERP modulation, namely an increased negativity for non-native compared to native rules. Orienting responses, albeit for visual attention, were furthermore found to vary in aging (Erel & Levy, 2016). A recent fMRI study (Geerligs, Saliasi, Maurits, Renken, & Lorist, 2014) showed increased brain activations (as compensatory mechanism) associated with more orienting of attention to distractors compared to target stimuli in elderly subjects due to the decreasing ability to suppress irrelevant information. A similar orienting response might have driven both the elderly data in Experiment 2 as well as the infant data in Experiment 5. Future studies will have to investigate whether this is a pure age-related effect or whether task and/or stimuli differences might also direct attention to different types of information and thus modulate the N400 amplitude.

In Experiment 1, fNIRS results showed increased activations for phonotactically native pseudowords (analogously to the increased N400 amplitude in the EEG) in left-hemispheric brain regions. These results are perfectly in line with predictions from the *Dynamic Dual Pathway Model* (Friederici & Alter, 2004) or the more acoustically oriented *Multi-Time Resolution Hypothesis* (Poeppel et al., 2008) predicting stronger left-hemispheric recruitment for segmental linguistic information or fast varying temporal modulations (both characterizing phonotactics). Comparing these lateralized topographical results in adults with the small and bilaterally distributed effect of phonotactics (present only at posttests as well as at day 3 of the training session) found in 6-month-olds of Experiment 5, we can conclude that lateralization can be an index for maturation. An adult-like lateralization was found to establish after 12 months of age when words were presented in isolation (Minagawa-Kawai et al., 2007) even though a successful discrimination between lexically relevant linguistic information was already possible at 6-7 months but recruiting bilateral brain regions at this young age.

The bilateral recruitment can be considered a compensatory mechanism often also found in children with speech disorders such as specific language impairment (Rinker et al., 2007) or dyslexia (Zhang et al., 2013). Such a bilateral recruitment is considered an inefficient strategy because duplication of brain areas supporting a specific function wastes neuronal resources and increases the risk for interhemispheric conflict (Corballis, 2009; Ringo et al., 1994). Thus, although such compensatory mechanisms are necessary for example in the immature infant brain or during speech impairment, they are less efficient than a unilateral adult and healthy lateralization. In Article 1 we specifically analyzed the issue of lateralization during infancy and came to the conclusion that lateralization is also impacted by the context in which the linguistic information, leading to a lateralization in adults, is integrated. When the context is facilitating such as in sentences or stimuli of longer duration, the relevant linguistic information is easier to be extracted and processed and this can lead to an adult-like hemispheric lateralization also in newborns or infants during the first months of life (Dehaene-Lambertz et al., 2002; Homae et al., 2006; Peña et al., 2003; Telkemeyer et al., 2009), thus earlier as observed in reduced context such as when words are presented in isolation. In this regard, we are currently conducting a study in 18- and 24-month-old infants listening to phonotactically native and non-native pseudowords in order to see whether at an older age, when also speech productive abilities are boosted, an adult-like lateralization can be attested.

Returning to brain areas recruited during language-specific phonotactic processing in Experiment 1 we found a fronto-temporal network in adult subjects. Despite the limited spatial resolution of fNIRS this topography coincides with findings from the innovative EEG/voxel-based-lesion mapping approach adopted in Experiment 2. This approach correlates ERP modulations with the voxel-wise location of lesions in patients. Correlations indicate which brain regions support a specific linguistic process investigated during the EEG experiment. Results showed that the middle temporal gyrus (MTG) highly correlated with the discriminatory ability between language-specific phonotactic processing, whereas posterior temporal and inferior parietal areas including supramarginal (SMG) and angular gyrus (AG) were responsible for the universal phonological preference contrast. These brain areas are part of the language network found in previous studies (Hickok & Poeppel, 2007, 2015; Skeide & Friederici, 2016; Vigneau et al., 2006). Only few neuroimaging studies so far specifically investigated phonotactic processing. One fMRI study investigated phonotactic probability in existing words while subjects performed a lexical decision task (identifying pseudowords within a list of real words) and found activations in inferior frontal areas (Vaden et al., 2011). We interpret these differences with respect to task and stimulus characteristics. In Vaden et al. (2011) more semantic control mechanisms were triggered. These usually are found in prefrontal brain areas (Badre et al., 2005). Crucially, even though phonotactics is a phonological cue in Experiment 2 it does not activate a classical phonological network, usually including STG/STS (Binder, 2017; Hickok & Poeppel, 2007). The found activation in MTG suggests that lexico-semantic processes are at the basis of phonotactic processing (Binder et al., 1997; Rissman et al., 2003). This makes sense if we consider the important role of phonotactics for lexical access and thus for word learning. Furthermore, the MTG is part of the ventral stream between temporal and frontal regions and is assumed to be involved in mapping sound to meaning (Friederici, 2015; Hickok & Poeppel, 2015).

The differentiation of universal constraints, on the other hand, revealed the recruitment of parietal areas being part of the dorsal stream to frontal areas. This pathway was found to be relevant for auditory-motor integration during speech production (Hickok & Poeppel, 2007, 2015), but also during phonological processing (Sarubbo et al., 2015), and combinatorial processing as reflected by the Merge principle (Friederici, 2015; Zaccarella et al., 2017). This is in accord with the idea that reversed speech in contrast to forward speech violates universal phonological well-formedness, contradicting the preferred sonority profile of languages (Berent, 2013). A recent fNIRS study showed that already newborns were able to differentiate between preferred and dis-preferred sonority profiles (Gómez et al., 2014).

7.2 Word learning from infancy to adulthood

Word learning employs several different strategies to fulfil the task of memorizing new lexical entries in order to be used during further speech comprehension or speech production. We are able to learn new words by means of passive acoustic exposure to the new language (Citron et al., 2011) but also through *fast mapping* (Carey & Bartlett, 1978), that is, the association of new words for specific objects. Furthermore, we can also make use of socio-pragmatic cues in order to improve our word learning mechanisms.

In both passive listening as well as fast mapping *statistical learning* is a very important operative mechanism. It describes that what is repeatedly presented according to specific rules is successfully learned (Aslin, 2017; Saffran et al., 1996). Statistical learning was found to function already in newborn infants (Gervain et al., 2008; Teinonen et al., 2009).

Word learning during infancy differs from word learning in adulthood, depending on several factors such as the maturation of the brain, pre-established knowledge about linguistic rules, objects, and words, and perceptual changes. At birth, infants are prepared to learn all the languages of the world (Eimas et al., 1971; Sebastián-Gallés, 2006, 2007; Werker & Yeung, 2005). Thus, they were found to be able to differentiate between different phonemes of non-native languages. This sensitivity, however, undergoes *perceptual narrowing* during the first year of life ending in an increased sensitivity for native contrasts and a decreased sensitivity for non-native contrasts which are not relevant for the infants' ambient language (Kuhl et al., 2008; Werker & Tees, 1984). Thus, bearing in mind perceptual narrowing and the *critical period hypothesis* (Lenneberg, 1967) postulating that language can only be acquired in specific temporal windows, we might assume that adults are not able to learn foreign languages. However, studies show that this is not the case. Some studies indicate that neuronal processing mechanisms are very similar to those of first language processing, even for quite complex linguistic functions such as syntax (Rossi et al., 2006). In Experiment 3 and 4 we focus on the investigation of very initial language learning mechanisms while adults learn new words corresponding to native phonotactic rules or not.

In Experiments 3 and 4 we specifically investigated the impact of two different language trainings on neuronal changes of native and non-native phonotactic processing in adults. In Experiment 3 the training consisted in the repetitive acoustic exposure to native and non-native pseudowords and thus resembles a passive listening condition. In Experiment 4, subjects participated in a semantic categorization training in which native and non-native pseudowords were arbitrarily combined to a category A or B. Subjects had to press a button after each heard pseudoword indicating whether they thought it belonged to category A or B. Feedback was provided in order to initiate a protosemantic learning. The aim of these experiments was to test whether adults are flexible enough to learn foreign language rules, in our case foreign phonotactic rules. We measured ERPs in order to track fast dynamic changes of lexical processing, indexed by the N400 component.

For native phonotactic rules, results showed a decrease in N400 amplitude irrespective of the training setting. This indicates that familiar linguistic rules get more automatized with increasing exposure due to the facilitated lexical access (Kutas & Federmeier, 2011). Non-native rules, on the contrary, showed a differential modulation in dependence of the training they were exposed to. For the passive listening training of Experiment 3, again a decrease in N400 amplitude was found. This suggests similar to the results of Experiment 1 that non-native rules which are not relevant for the native language are discarded and treated as nonwords. Such a mechanism is reasonable at the very beginning of a learning process when the discrimination of relevant and irrelevant information is given priority. Such a mechanism, however, does not allow the actual encoding of new information in the lexicon. Evidence for such processes was found in Experiment 4 which introduced a semantic categorization context. In this experiment the N400 decrease for non-native pseudowords was abolished and partially turned into increased amplitudes suggesting that lexical integration processes started. A similar increase in N400 amplitude was obtained in an MEG study training pseudowords consisting of non-native phonemes in combination with real objects (Dobel, Lagemann, et al., 2009). The difference between our Experiment 4 and the study of Dobel, Lagemann, et al. (2009) is that we provided a very restricted protosemantic context in which the categorization task was arbitrary and did not relate to the phonotactic information. Dobel, Lagemann, et al. (2009), on the contrary, investigated a classical second language learning paradigm, in which the objects and the names of the objects are already known in the subjects' native language and only the new name in the foreign language has to be learned. Such a context is much easier and represents a classical semantic context in which several new words are combined to concrete objects. The found neuroplasticity changes are fascinating because they indicate that even though adults have been subject to perceptual narrowing long ago they are still able to initiate foreign language learning processes. The striking finding is that they can perform this in a very fast way (i.e., after only two short training sessions) and even when only a very minimal semantic context is available.

These results have some implications for educational sciences as they indicate that passive listening alone is relevant for identifying relevant material which has to be learnt but at least a minimal semantic context initiates semantic processing and thus leads to the integration of new words into the lexicon.

In Experiment 5, fast mapping abilities in young infants were in the focus of investigation. In particular, pseudowords corresponding either to phonotactic rules of the infants' native language or to an unknown language, were combined in an associative training with pseudoobjects. Thus, infants had to learn both the word form and the object shape and associate them to be successfully stored in memory. We chose 6-month-old infants as they are prelingual, thus not influenced by speech production mechanisms often boosting also speech perceptual abilities, because they are in the midst of the associative learning phase, and because perceptual narrowing is assumed to not exert such a strong influence as in older infants during the second year of life. Nevertheless, perceptual narrowing with respect to phonotactic rules has already started as could be attested by a small but reliable differential neuronal processing between native and non-native rules. With respect to learning, 6-month-old infants showed a robust increase in amplitude with respect to a frontally distributed negativity in the EEG as well as an increase in activation in the fNIRS. This modulation was predominantly visible for native and non-native rules suggesting that even though perceptual narrowing has started it does not seem to compromise learning. Infants at this young age seem to be equally open for learning native and non-native regularities. This finding is in contrast to assumptions that infants can only learn new word-object associations when words conformed to native language rules (Graf Estes et al., 2011; Graf Estes, 2014; Graf Estes & Bowen, 2013). However, these infants were 14 to 19 months old, thus exposed to the native language much longer than our 6-month-olds. These findings suggest that the brain is exceptionally flexible at a young age and learning mechanisms are subject to influences from previous linguistic experience from very early on. Thus, the earlier a foreign language is acquired the better it can be consolidated as an additional native language in the brain and true balanced bi- or multilingualism arises.

As previously mentioned the EEG results in Experiment 5 elicited a frontally distributed negativity. The amplitude of this negativity (often referred to as N200-500) in young infants was shown to be increased when familiarity of word forms increases through repetitive exposure, both through passive listening or an associative-semantic context (Friedrich & Friederici, 2005, 2008, 2011, 2017, Kooijman et al., 2005, 2013, Mills et al., 1993, 2005; Torkildsen et al., 2009). In Experiment 5 an increased frontal negativity was found during posttests compared to pretests as well as for trained compared to untrained items signaling similar familiarity effects. Thus, this negativity represents a component reflecting the audio-visual integration of the associative link supported by memory encoding processes (Bauer et al., 2006; Borgström et al., 2015). This means that the word forms are analyzed on a phonological basis and stored in memory. But this frontal negativity does not represent semantic integration per se. The latter was found to elicit a centro-parietally distributed N400 leading to reduced amplitudes when access to the lexicon is facilitated (Friedrich & Friederici, 2005, 2008, 2011, Torkildsen et al., 2008, 2009, 2007). Because infants are at the very beginning of their language learning course they have to learn the single word forms, the single objects, and the associative link between them. These mechanisms are different from adult learning mechanisms which usually have the objects already stored in memory and only have to learn the new word form in association to the known object. Furthermore, adults are influenced by linguistic knowledge from their native language which can be supportive for learning in the foreign language as some overlap in regularities occurs between languages but can also cause conflict in case of diverging regularities.

Neuronal modulations of Experiment 5 were found for both trained and untrained items suggesting that generalization processes are active already in such young infants. Generalization is important as we do not have the computational capacities to store each single rule for a specific type of information but we have to be able to apply the learned abstract rules to new information. Such a mechanism was also postulated for the *Merge* principle affecting also phonological processing and word learning (Yang et al., 2017). Generalization mechanisms are furthermore indispensable during re-acquisition of language after a brain lesion when patients undergo a laborious rehabilitation process.

Learning effects observed in 6-month-olds in Experiment 5 were observed from pretests to posttests, thus at a short-term basis. The design adopted on three consecutive learning days would have been able to detect also long-term learning effects building up over several days. However, we failed to identify such long-term effects. Previous studies showed that long-term retention in memory is fragile at this young age (Friedrich & Friederici, 2011). Even though no overnight consolidation effects were ascertainable, a recent paper discusses the potential role of sleep for long-term retention (Friedrich et al., in press). Future studies will have to provide more detailed information about the developmental trajectory of the intriguing interaction between memory and language.

Beneficial overnight consolidation effects on long-term retention of new words was found in adults (Davis et al., 2008). The design of Experiment 3 and 4 in our adult participants also allowed assessing potential overnight consolidation effects. A closer look at the data revealed that especially the passive listening training led to overnight consolidation effects after the first training on day 1. Reductions in N400 were found first occurring from posttest of day 1 to pretest of day 2 and afterwards establishing further at day 2 and 3. For the categorization training and especially for the induced increase in N400 for non-native rules no such overnight consolidation effects were visible as this increase was predominantly present at a short-term range at day 3. This indicates that passive exposure is affected by overnight consolidation to a greater extent than a demanding categorization training.

In Experiment 5, not only EEG but also fNIRS was assessed in order to provide more insights into lateralization in the developing brain. An adult-like lateralization when segmental linguistic information was presented in single words was found no earlier than 12 months of age (Minagawa-Kawai et al., 2007). This was attributed to immature neuronal mechanisms being supported by bilateral brain areas at this young age. In Experiment 5 we aimed at investigating whether a more adult-like left-hemispheric lateralization may be elicited by an intense word learning setting. Indeed, for the massive short-term learning effect a stronger left-hemispheric recruitment was found suggesting that linguistic rather than acoustic or domain-general processing mechanisms are in progress. For the modulation of trained compared to untrained items as well as for the comparison between native and non-native rules the involved brain areas, however, recruited bilateral areas suggesting that duplication of functions in both hemispheres is though necessary, probably for compensating for immature neuronal circuits (Corballis, 2009; Ringo et al., 1994). In Article 1 we discussed that not only immature neuronal substrates may account for these lateralization differences but also the facilitating context. It would be thus interesting to investigate 6-month-olds in a similar associative learning setting but presenting native and non-native regularities in a sentential context. If sentences facilitate word learning then a stronger left-hemsipheric lateralization should be observable already at this young age. If, however, biology is the driving force, a still bilateral recruitment should be present.

Compensatory mechanisms were found to manifest at the neuronal level not only in abnormal lateralization but also in a differential recruitment of anterior and posterior regions. In particular, studies showed that when task demands increase or posterior regions do not work properly due to several reasons (e.g., speech pathology, lesion, immaturity, or aging), more frontal brain areas are recruited as a compensatory mechanism. Interestingly, also during aging such a posterior-to-anterior shift was found and integrated into the *posterior-anterior shift in aging* (PASA) model (Davis et al., 2008) postulating age-related increases in frontal activity at the expense of a reduction of activity in posterior brain areas. Experiment 1 and 2 revealed more posteriorly oriented brain areas, particularly located in the temporal cortex, to support phonotactic processing. This is astonishing for elderly patients (Experiment 2) having suffered a brain lesion but explainable because also their symptomatology was already regressed in the chronic phase. Taking this posterior-to-anterior shift into consideration in our infant data of Experiment 5 we clearly observe such compensatory mechanisms as learning effects were found not only at posterior regions but were shown to recruit additionally wide areas of the frontal cortex. Thus, not only lateralization but also a regional shift may indicate immature processing mechanisms in the infant brain.

In the same vein of reasoning, a regional shift was proposed for the bilingual brain. The bilingual *anterior-to-posterior and subcortical shift* (BAPSS) (Grundy et al., 2017) describes an increased neuronal efficiency in bilingual individuals reflected in more intact posterior regions not necessitating the reliance on frontal areas (Abutalebi et al., 2012; Waldie et al., 2009). BAPSS postulates that in aging bilinguals posterior regions are less subject to impairments and thus can be solely used without the necessity of additional frontal recruitment as compensatory mechanisms often observed in monolingual elderly (Gold et al., 2013; Grant et al., 2014). In bilingual young children, usually an over-recruitment of frontal brain areas is observed because two languages have to be kept in mind and this posits higher computational demands compared to monolingual children (Jasinska & Petitto, 2013; C. Kobayashi et al., 2008; Mohades et al., 2014). However, during advanced development this over-recruitment of frontal areas reduces and an adult-like posterior dominance appears (Grundy et al., 2017). In Experiment 6 investigating monolingual and bilingual 5-year-old children an adult-like processing could already be attested. The only activation found during adjective learning by means of gestures was in the right superior temporal sulcus (STS). No additional recruitment of frontal regions was observable. STS was found to be involved in the intentional communicative network and to play a role when socio-pragmatic cues are used during word learning (Deen et al., 2015; Doré et al., 2015; Kobayashi et al., 2007; Yang et al., 2015). The larger activation in this area for bilingual children suggests that they can better use socio-pragmatic cues (Colunga et al., 2012; Farhadian et al., 2010; Greenberg et al., 2013; Yow, 2015; Yow & Markman, 2011). The innovative finding of Experiment 6 is not only that such a bilingual advantage is evidenced by more efficient neuronal processing mechanisms, but also that it occurs already during childhood and more importantly during a challenging word learning task. Thus, when task demands increase, bilingual children seem to better handle with these difficulties. Such domain-general cognitive advantages in bilinguals led recently to the assumption that bilingualism can be a *cognitive reserve* during aging. This idea is based on findings showing that bilinguals exhibit a delayed onset of dementia of 4-5 years (Alladi et al., 2013; Bialystok, Craik, & Freedman, 2007; Chertkow et al., 2010; Craik, Bialystok, & Freedman, 2010; Schweizer, Ware, Fischer, Craik, & Bialystok, 2012; Woumans et al., 2015) and a generally reduced risk for cognitive decline (Perquin et al., 2013; Wilson, Boyle, Yang, James, & Bennett, 2015) compared to monolinguals, probably guided by more efficient neuronal mechanisms. This emphasizes the role of bilingualism as a potential neuroprotective factor.

7.3 Multi-methodological approaches and limitations

The experiments presented in the present habilitation treatise included different combinations of methods. The importance of such multi-methodological approaches becomes evident for example in Experiment 6 in which behavioral results did not reveal any difference between bilingual and monolingual children, whereas fNIRS did. In Experiment 1 and 5 partially concordant results were achieved for EEG and fNIRS with respect to the discriminatory ability or the direction of learning effects but though methodological differences were present leading to a better understanding of the underlying neuronal mechanisms. FNIRS provides a better topographical resolution which proved to be relevant in Experiment 1. Adult participants showed amplitude modulations in the N400 component in the EEG. However, the N400 does not show a clear lateralization. The simultaneous application of fNIRS allowed identifying a clear left-hemispheric network underlying phonoatctic processing. This is even more important for findings in the developing brain, as lateralization can be an index of maturation. In Experiment 5 the short-term learning effect in 6-month-old infants showed a predominantly left-hemispheric lateralization in the fNIRS. Such a lateralization could not be attested by means of EEG which revealed a bilateral frontal effect. On the other hand, EEG is more sensitive to disentangle fast dynamic changes. In the developing brain either frontal negativities or centro-parietal N400 modulations were found with respect to lexico-semantic processing. Whereas the former are considered to be more relevant during initial learning mechanisms and reflect familiarity effects supporting the encoding into memory, the N400 resembles the access to the lexicon when memory encoding already has taken place. Thus, the underlying processes can also be evaluated on the basis of which ERP component is observable at which developmental stage.

These examples evidence the importance of multi-methodological approaches in order to get clearer insights into the complex machinery of neuroplasticity.

In Experiment 2 an innovative EEG/voxel-based lesion mapping was applied. Again, the accordance between different neurophysiological mechanisms can be used for the sake of a better understanding of the brain. Critically to this study can be mentioned that only the left hemisphere was analyzed. It is well known that several neuroplastic changes occur after a brain lesion, some of these spontaneously, others induced by intensive rehabilitation. These changes also involve the take-over of linguistic functions by the homologous right hemisphere as compensatory mechanisms. Thus, future studies may have to address also the role of the right hemisphere in patients affected by a left-hemispheric lesion, with respect to several linguistic aspects including phonotactics.

Methods such as fNIRS have some feasibility advantages, compared to fMRI, as they can easily be applied in young infants and in beside applications in patients due to the more natural experimental environment without a fixed scanner, because it lacks instrumental noise thus making it more suitable for the investigation of fine-grained auditory stimulation, and because it does not interfere with other neurophysiological methods such as EEG. Despite these advantages, it should be noted that each method has its limitation. FNIRS provides a limited spatial resolution compared to fMRI. Thus, if a high spatial resolution is needed, fMRI is definitely the better choice. Thus, the best suitable method for a specific research question should be selected and if possible a combination of several methods aspired to. This was the overarching attempt in the studies included in the present habilitation treatise.

8. Conclusions and perspectives

The studies presented in this habilitation treatise evidence that differential word learning mechanisms are active during infancy, childhood, adulthood, and in patients after a brain lesion. In particular, infants were found to be very flexible and open when learning non-native linguistic cues. However, the brain areas were found to be immature at this young age and to undergo several developmental changes until they reach an efficient adult-like level. On the other hand, adults were also found to be flexible enough to learn rules of a foreign language. In particular, a beneficial effect of a semantic learning context could be attested leading to the integration of the newly learned rules in the lexicon. Finally, the impact of bilingualism for developing efficient neuronal strategies was attested already during childhood. These findings are relevant not only for neuropsychological and experimental disciplines but have implications also for educational sciences as the optimal learning setting for a specific foreign language learner during infancy or adulthood might be arranged according to neuroscientific considerations.

The present findings provide the basis for subsequent studies investigating for example early neuronal markers for language disorders. Lateralization can be a marker for immaturity and often an abnormal lateralization was found in language disorders such as specific language impairment, dyslexia, stuttering, or premature infants exhibiting an elevated risk for developing later language disorders. Currently, two projects are in progress aiming at identifying early neuronal markers of language processing in infants at-risk for dyslexia as well as in premature infants. Finding differences at the neuronal level during infancy, thus before the actual manifestation of the disorder, opens a lot of possibilities for early intervention programs minimizing the negative effects of these disorders for the subsequent development of the child.

Findings of the present experiments further contribute new insights into the understanding of efficient neuronal mechanisms. Bilingualism for example was found to lead to more efficient recruitment of posterior brain areas, also during challenging tasks. Other studies propose that bilingualism represents a neuroprotective factor during aging. To follow up this idea I have currently a project in preparation aiming at the investigation of such a potential neuroprotective effect of bilingualism during language disorders.

Finally, some patients are faced with a sudden hearing loss. Which neuroplasticity mechanisms guide language processing under these adverse conditions (for example in hearing-impaired patients supplied by a cochlear implant which enables hearing but with strong limitations) is currently addressed in a neuroscientific study of my lab on speech comprehension in cochlear-implant patients.

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Appendix: Articles from empirical part

Permission for reprinting the articles included in this habilitation treatise was granted by the publishers.

Rossi, S., Telkemeyer, S., Wartenburger, I. & Obrig, H. (2012). Shedding light on words and sentences: Near-infrared spectroscopy in language research. *Brain & Language, 121,* 152-163. doi: 10.1016/j.bandl.2011.03.008

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https://www.cambridge.org/core/journals/bilingualism-language-and-cognition/article/bilingual-and-monolingual-children-process-pragmatic-cues-differently-when-learning-novel-adjectives/C93A80497517BDA5E4F3A1C6DB7B9DF3